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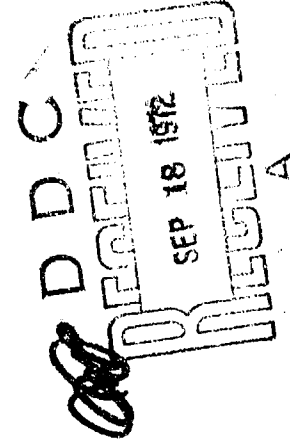
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ADVANCED CONTROLS TECHNOLOGY

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THE **BOEING** COMPANY
WICHITA DIVISION - WICHITA, KANSAS 67210

JANUARY 1971
D3-8466



IG700988-1

CONTENTS

INTRODUCTION	1
B-52 ECP 1195 STABILITY AUGMENTATION SYSTEM	4
LAMS	14
AEROELASTIC MODELING	24
SST	26
STOL	36
CCV	40
Flutter Control	42
Ride Smoothing	50
Maneuver Load Control	56
Augmented Stability	60
CONCLUSION	65
REFERENCES	67

INTRODUCTION

Results of recent Boeing-Wichita analytical studies and flight demonstrations have shown the potential of advanced controls technology to significantly improve aircraft performance. Through proper selection of control surface and sensor locations, the control system can be designed to:

- Reduce structural fatigue damage rate
- Reduce turbulence induced loads
- Increase flutter speed
- Reduce accelerations within the crew and passenger compartments
- Reduce wing loading during maneuvers
- Augment basic aircraft stability

Application of advanced control concepts during aircraft design can result in reduced weight, increased payload, increased range, and improved ride and handling qualities.

This document summarizes results of recent Boeing-Wichita activities in these areas. The references listed on pages 65 through 70 provide additional information on these activities.

The Air Force initiated CCP 1195 study in 1964 following a B-52 vertical tail structural failure during low level flight through turbulence. The study was conducted to determine the feasibility of reducing B-52 structural fatigue and improving controllability in turbulence with an advanced flight control system. The program has progressed through prototype development and flight test, and the system is currently being installed on the B-52 G/H fleet.

A Load Alleviation and Mode Stabilization (LAMS) program was initiated in 1966 under the direction of the Air Force Flight Dynamics Laboratory to demonstrate the capability of an advanced flight control system to alleviate gust loads and control structural modes using conventional aerodynamic control surfaces and to develop analytical techniques and criteria for future LAMS systems. This program was completed in 1968.

Boeing-Wichita has assisted NASA Langley Research Center since 1967 in developing advanced flight control system concepts for aeroelastic models. Work is currently underway to develop control systems for B-52 and SST models.

A program was initiated in 1967 to apply advanced control techniques to the SST. This experience was applied also to the B-1 during the Boeing proposal effort.

During early 1970, the Air Force Flight Dynamics Laboratory contracted Boeing-Wichita to conduct a study to determine the feasibility of demonstrating a flutter stability augmentation system (SAS) on the B-52 LAMS flight test airplane. This study is currently underway.

A study was initiated in late 1970 by NASA Langley Research Center for preliminary design of a low wing loading STOL transport employing advanced controls concepts for ride smoothing. This work will be completed in January 1971.

As a result of the LAMS program and subsequent analytical studies, an unsolicited proposal has been submitted to the Air Force Flight Dynamics Laboratory for a Controls Configured Vehicle flight demonstration program. This program is expected to be initiated in 1971.

BOEING-WICHITA EXPERIENCE IN ADVANCED CONTROLS TECHNOLOGY

1964	1965	1966	1967	1968	1969	1970	1971
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B-52 CCP 1196 STUDY

B-52 ECP 1196 PROTOTYPE DEVELOPMENT AND FLIGHT TEST KIT DESIGN AND FLIGHT TEST FLEET INSTALLATION

AFFDL LAMS CONTRACT ANALYSIS AND FLIGHT TEST

NASA-LANGLEY AEROELASTIC MODEL CONTRACT DESIGN ANALYSIS AND TEST

SST ANALYSIS AND SIMULATION

B-1 ANALYSIS ANALYSIS
AFFDL FLUTTER SAS CONTRACT

ANALYSIS
NASA-LANGLEY STOL CONTRACT ANALYSIS

ANALYSIS AND FLIGHT TEST
AFFDL CCV CONTRACT

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B-52 ECP 1195 STABILITY AUGMENTATION SYSTEM

(References 1-20)

The B-52 was designed as a high altitude bomber, but mission requirements were later expanded to include low-altitude, high-speed flight. Increased turbulence of the low altitude environment results in larger peak loads, increased fatigue damage rates and reduced controllability. Severity of the low level environment is vividly illustrated by this B-52H following a severe turbulence encounter in the southeastern Colorado area. The accident occurred on B-52H, AF 61-023 while engaged in dynamic load survey testing on January 10, 1964.

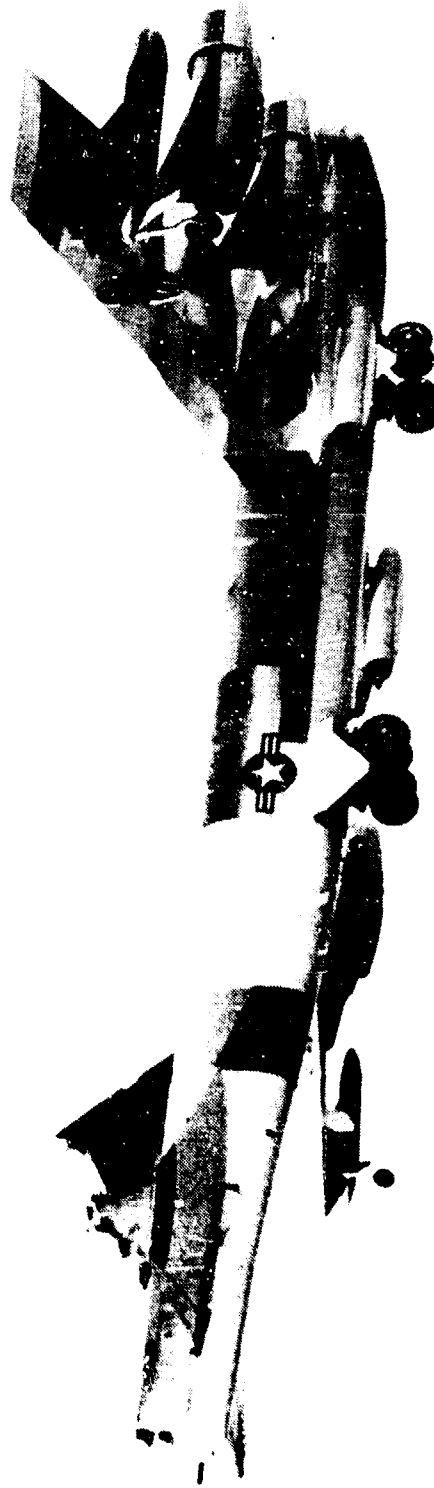
The airplane was extensively instrumented, and data was being recorded during the severe turbulence encounter. Based on analytical reconstruction of the gust profile, maximum vertical gust velocities were 78 fps upward and 48 fps downward. Maximum lateral gust velocities were 104 fps from right to left and 55 fps from left to right. The airplane yawed away from the gust, and the dynamic overswing of the airplane, combined with a sudden reversal of the gust, resulted in a condition that exceeded the vertical tail design strength.

This incident and recommendations from an ASD Special Committee on Aeronautical Design Practices and Criteria (Ashley Committee) emphasized the need for an advanced flight control system on the B-52. The B-52 ECP 1195 Stability Augmentation System (SAS) program was initiated to:

- Reduce the probability of aircraft loss by reducing loads and increasing safety,
- Improve handling qualities,
- Provide a margin for unpredictable structural problems resulting from uncertainties inherent in airplane life prediction methods and airplane usage planning.

The ECP 1195 system uses existing rudder and elevator control surfaces with wide bandpass electrohydraulic actuators. Airplane angular rate and acceleration information are sensed, processed and fed to the actuators to reduce peak loads and fatigue damage rates. Typical improved damping of one aircraft structural mode is shown graphically on the next page.

B-52 LOW LEVEL GUST ENCOUNTER



IG700988-29

Damping of various structural modes with the SAS ON and OFF was determined during flight tests by exciting the structural modes with control surface sinusoidal motions. Control surface motions were controlled by an oscillator that could be varied in frequency, amplitude and number of cycles. The command to the surface actuator was manually tuned to excite only the selected structural mode. After a predetermined number of cycles, the commanded oscillation was stopped at exactly zero to prevent exciting structural modes other than the one being tested.

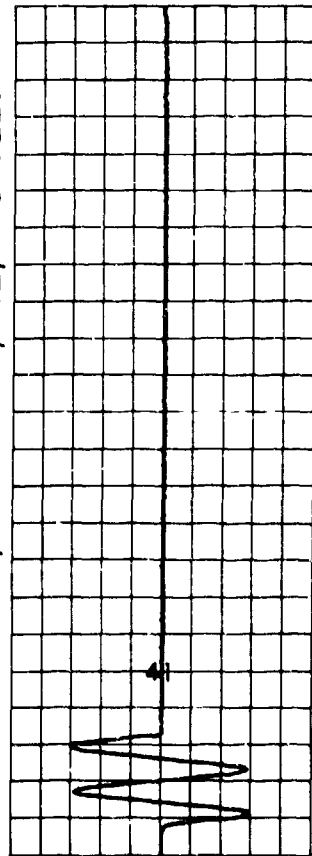
This chart shows a typical time history trace of a 1.4 cps aft body bending mode excited by two cycles of the rudder. The middle trace shows the unaugmented airplane in which the mode was allowed to decay after the two cycle excitation. The bottom trace shows damping of the mode with the SAS engaged. In this case, the SAS was engaged shortly after the rudder command was clamped to zero. Damping ratio of this structural mode at this flight condition exceeds 0.40 with the SAS.

FLIGHT TEST RESULTS EFFECT OF ECP 1195 SAS ON AFT BODY BENDING

250 KCAS, 300 KIPS, 22,000 FEET

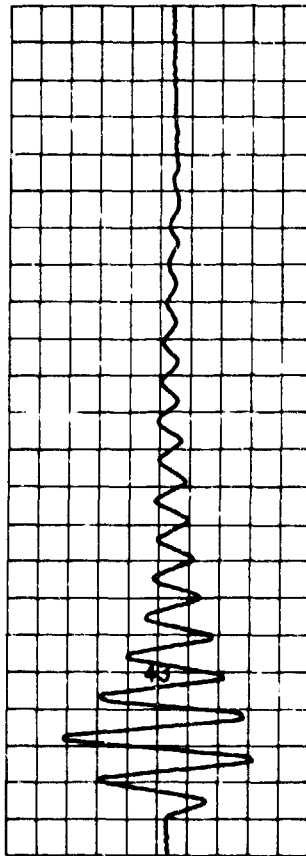
RUDDER
COMMAND

2° RUDDER COMMAND
2 CYCLES AT 1.4CPS



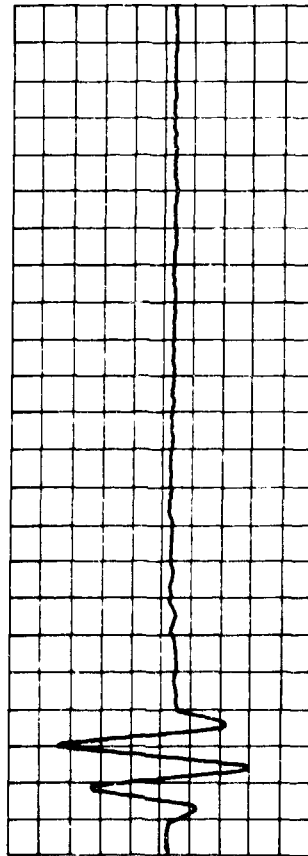
BODY
STATION 973
BENDING
MOMENT

SAS OFF



BODY
STATION 973
BENDING
MOMENT

SAS ON



← SAS ENGAGED

TIME →

The ECP 1195 SAS improved Dutch roll damping at all flight conditions, with the largest improvements at high altitude, heavy weight cruise conditions. Damping ratios were more than double for all flight conditions tested.

This trace of aft body side displacement was recorded with the SAS OFF and then ON while flying in turbulence. The pilot reported the turbulence levels in both cases were essentially the same. Aft body side displacement with the SAS OFF shows significant Dutch roll contributions. With the SAS ON increased Dutch roll damping reduces the response amplitude over 50 percent.

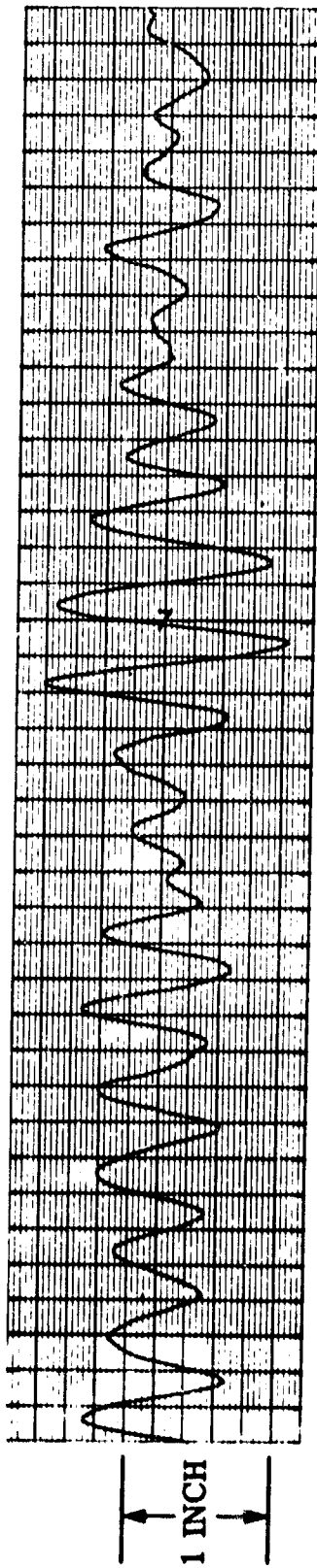
Random structural loads during flight tests were reduced in amplitude and frequency. Peak loads were reduced 30 percent on the body, 10 percent on the wing and 30 percent on the fin.

Analysis results showed fatigue damage rates at critical stations were reduced approximately 70 percent on the body, 20 percent on the wing, and 90 percent on the fin.

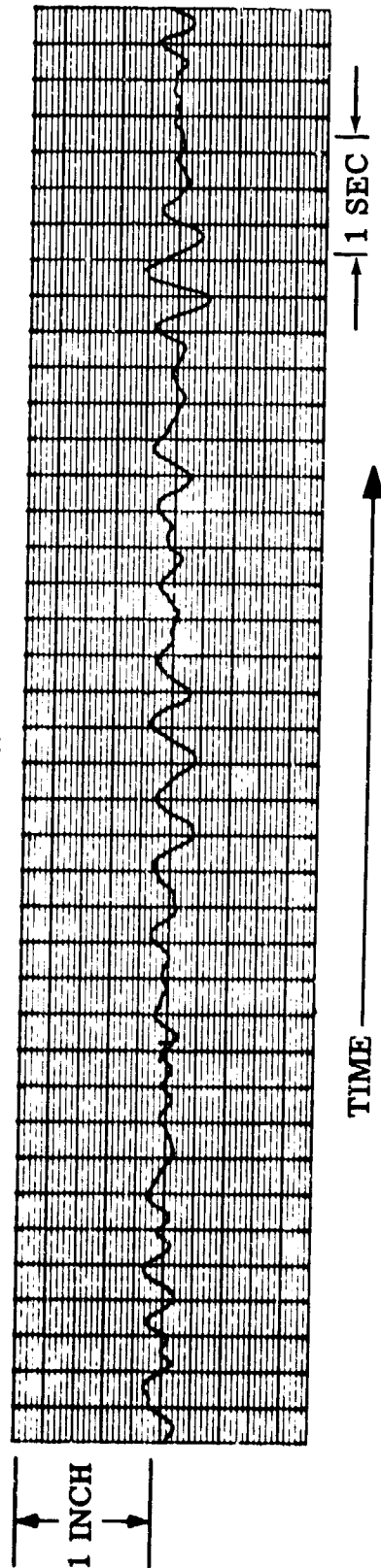
FLIGHT TEST RESULTS AFT BODY SIDE DISPLACEMENT IN RANDOM TURBULENCE

(BODY STATION 1655)

SAS OFF



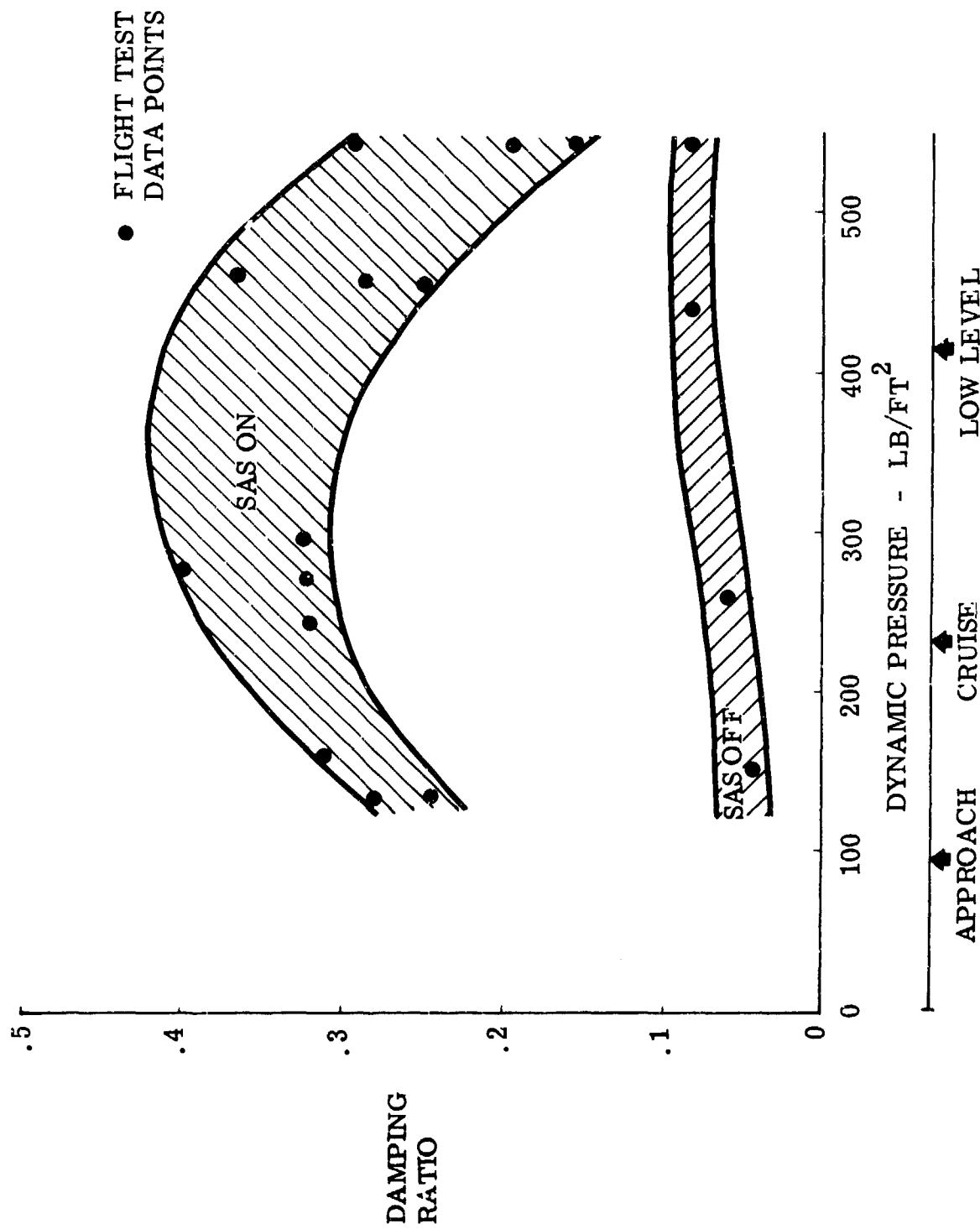
SAS ON



During ECP 1195 flight tests, aft body bending mode damping was measured at conditions representative of the B-52 flight envelope.

This chart summarizes results measured during approach, cruise, and low level conditions. Normal cg and gross weight variations were tested for each speed and altitude. As a result of SAS feedback gain scheduling with dynamic pressure, aft body lateral bending mode damping ratios were at least doubled for all flight conditions.

FLIGHT TEST RESULTS AFT BODY LATERAL BENDING MODE DAMPING



IG700988-17

In terms of fatigue damage and probable occurrence of overload, mission flexibility was significantly improved with the ECP 1195 SAS.

The upper portion of this table compares the time for a B-52H to accumulate a unit of fatigue damage while operating at low level at 350,000 pounds gross weight in the SEG environment (Reference 14) with and without improved stability augmentation.

For equal fatigue damage an airplane can:

- Fly 11 times longer with SAS than without SAS at 325 knots
- Fly 8.4 times longer with SAS than without SAS at 400 knots
- Fly 2.7 times longer with SAS at 400 knots than without SAS at 325 knots

The lower portion of the table compares the relative time to reach an overload occurrence for a B-52H operating at the above conditions.

For equal time to probable overload, an airplane can:

- Fly 1000 times longer with SAS than without SAS at 325 knots
- Fly 100 times longer with SAS than without SAS at 400 knots
- Fly 26 times longer with SAS at 400 knots than without SAS at 325 knots

MISSION FLEXIBILITY WITH ECP 1195 SAS

B-52G AND H FLEET
350,000 POUNDS GROSS WEIGHT
LOW LEVEL - SEG ENVIRONMENT

	SPEED	WITHOUT SAS	WITH SAS
TIME TO EQUAL FATIGUE DAMAGE	325 KEAS	1	11
	400 KEAS	0.32	2.7
TIME TO EQUAL OCCURRENCE OF OVERLOAD	325 KEAS	1	1000
	400 KEAS	0.26	26

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LAMS

(References 21-33)

The Load Alleviation and Mode Stabilization (LAMS) program was initiated in 1966 by the Air Force Flight Dynamics Laboratory to demonstrate the capability of an advanced flight control system to alleviate gust loads and to control structural modes on a large flexible aircraft using conventional aerodynamic control surfaces. The B-52 was selected as the test vehicle because its dynamic characteristics are representative of future generation large flexible aircraft and the extensive loads data available for the airplane.

The specific goal of the program was to flight demonstrate a measurable reduction in fatigue damage rate due to turbulence while retaining or improving existing aircraft handling qualities. In addition, a C-5A study was conducted to analytically demonstrate improved C-5A ride quality without appreciable sacrifice of fatigue damage rate improvements.

A B-52E airplane (NB-52E AF 56-632) was selected for the program, and the LAMS flight control system (FCS) was designed to use the existing aileron, spoiler, elevators and rudder control surfaces for force producers. The system was designed to operate at three typical flight conditions:

- A low level, high speed, high gross weight condition
- A low level, low speed, high gross weight condition
- A high altitude, cruise, medium gross weight condition

For comparison, a baseline SAS representing contemporary stability augmentation systems was designed to control only rigid body motions.

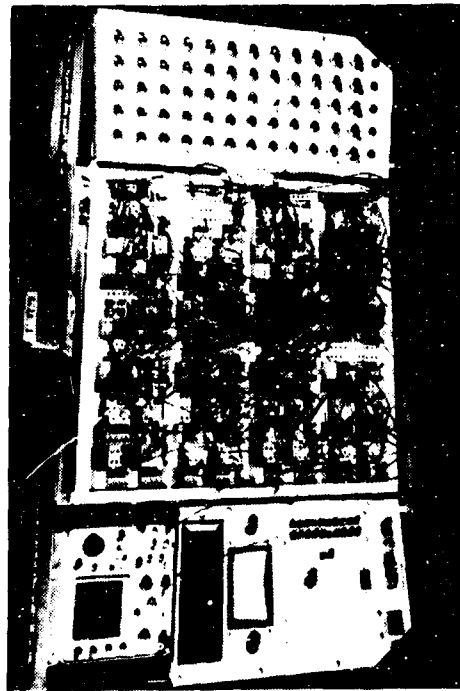
The test airplane pilot's station was converted to fly-by-wire (FBW) and the copilot's station to a safety monitor station. The Bomb-Nav station was modified to a flight engineer's station, with two TR-48 analog computers and associated LAMS FCS electronic equipment. A gust probe was installed on the airplane nose to correlate fatigue damage, bending moments and accelerations with atmospheric turbulence.

AFFDL LOAD ALLEVIATION AND MODE STABILIZATION (LAMS) PROGRAM



LAMS TEST AIRPLANE NB-52E AF 56-632

ON-BOARD TR-48 ANALOG COMPUTER



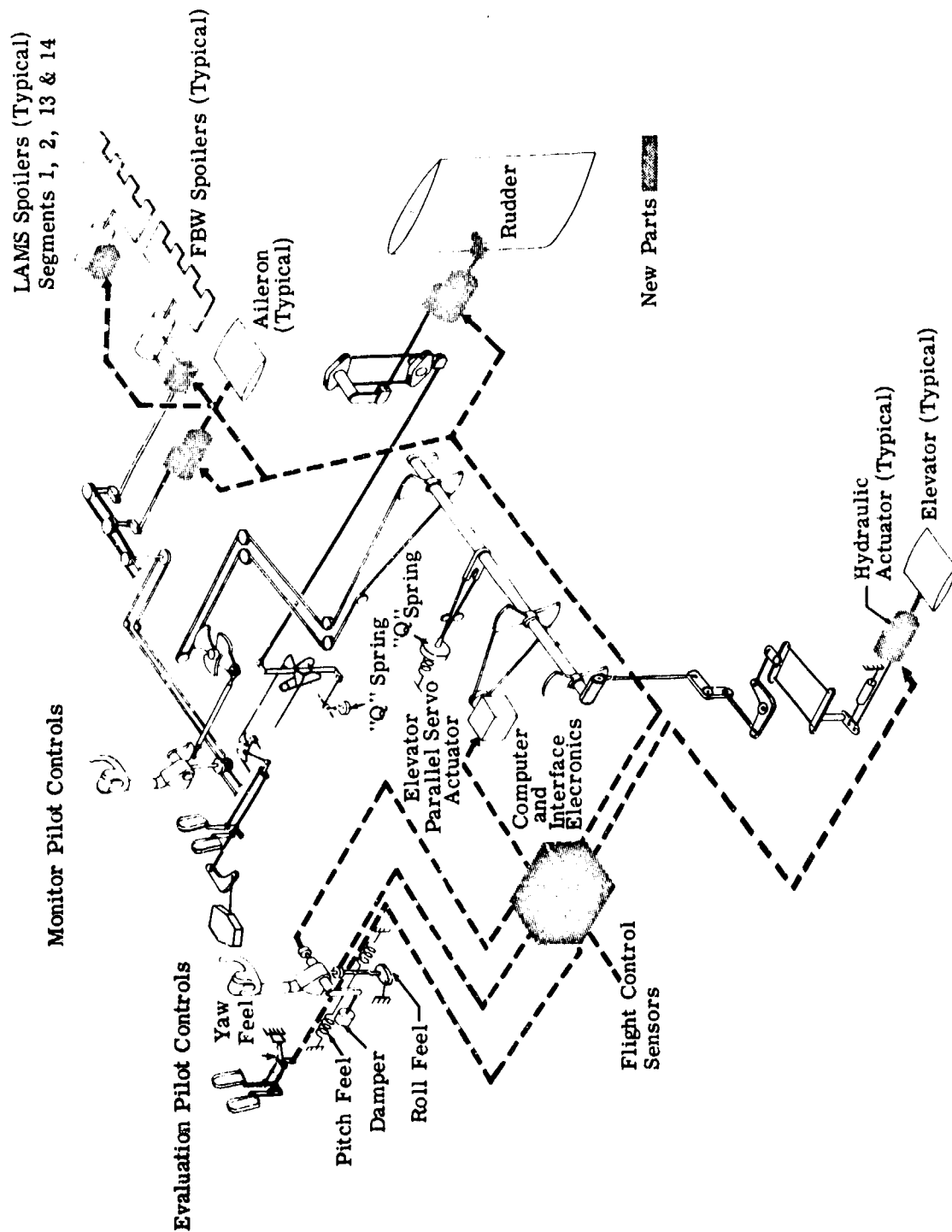
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The LAMS test airplane flight control system (FCS) was modified to incorporate wide bandpass electrohydraulic actuators on the elevators, ailerons and rudder that responded to mechanical and electrical commands. Integrated servo valves, that respond to mechanical, fly-by-wire (FBW) and airbrake inputs, were added to the inboard spoiler panel actuation system. Outboard spoiler actuators were modified to include a hydraulic servo valve commanded by the LAMS FCS. Installation of these components provided the airplane with all hydraulically powered surfaces and with an actuation system capable of receiving mechanical or electrical signals to all surfaces except the LAMS spoilers, which could only receive electrical signals.

The monitor pilot's wheel, column and rudder pedals were connected to the original control cables, providing mechanical inputs to the electrohydraulic surface actuators. The monitor pilot control inputs could override the evaluation pilot's commands in all axes.

The evaluation pilot was located at the pilot's station. The evaluation pilot's column, wheel and rudder pedals were disconnected from the normal cable configuration and connected to centering springs. Position transducers were attached to the controls to provide FBW command signals. FBW signals for the aileron, spoilers and rudder actuators were processed by the analog computer and sent to the surface actuators. The FBW column signal was processed by the computer and fed to the pitch autopilot parallel servo connected to the aft body elevator torque tube. In turn, this drove the mechanical system to command the elevator actuator. This mechanization forced the monitor pilot's column to follow the evaluation pilot's column which was the only monitor control that followed the evaluation pilot's inputs.

B-52 LAMS FLIGHT CONTROL SYSTEM



This chart compares analytical yearly fatigue damage rates for the basic aircraft (controls locked), baseline SAS and LAMS FCS for a mission composed of the three selected flight conditions. Effects of vertical, lateral and rolling gusts are included in the data. The LAMS FCS significantly reduces fatigue damage rates at wing stations (WS) and body stations (BS). Most of this improvement results from the longitudinal FCS.

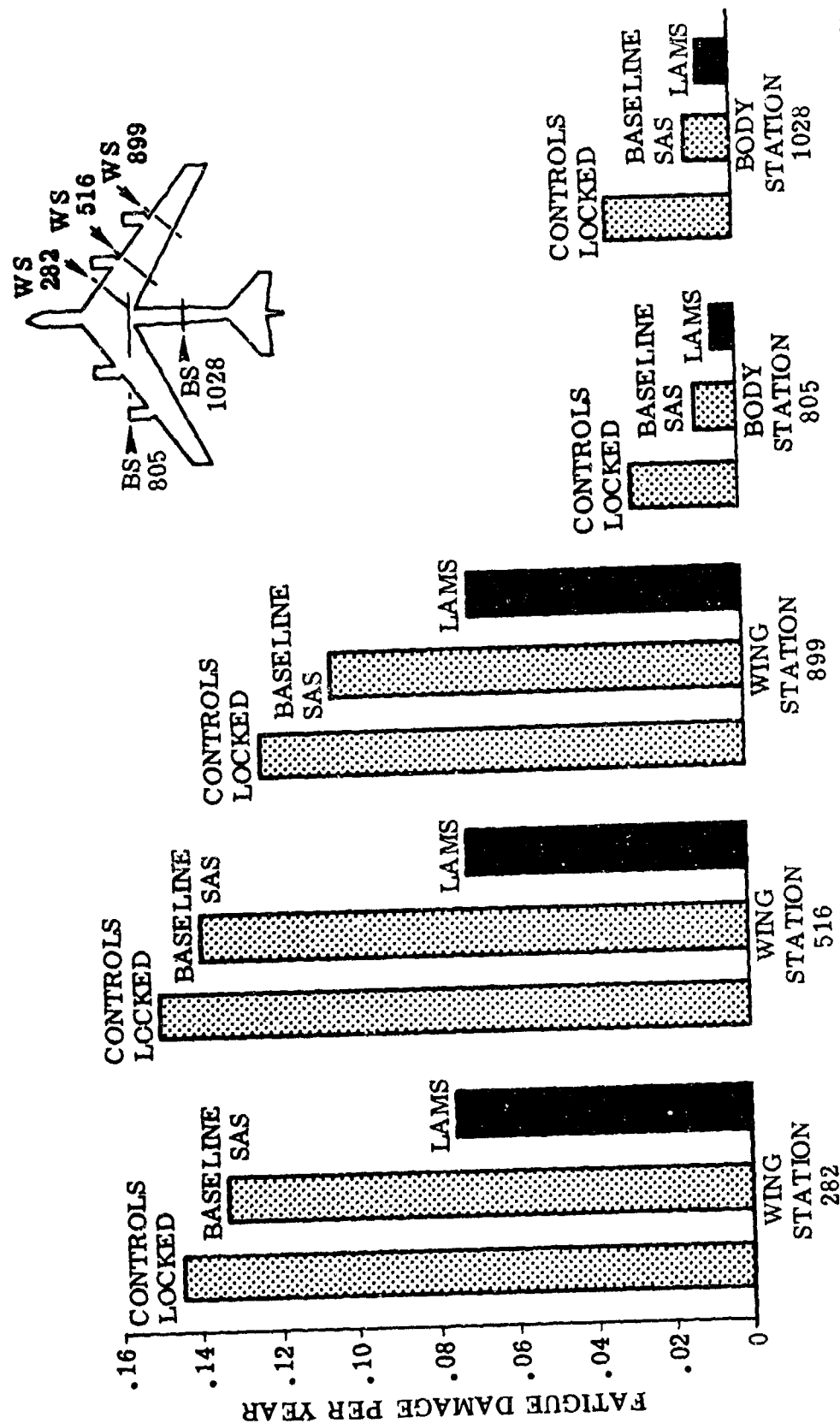
Fatigue damage rate contributions from each flight condition with the LAMS FCS are shown below:

STRESS LOCATION	DAMAGE PER HOUR			DAMAGE PER YR. *
	CONDITION 1	CONDITION 2	CONDITION 3	
WS 282	1.66×10^{-3}	0.846×10^{-3}	0.0025×10^{-3}	.0758
WS 516	1.45×10^{-3}	0.847×10^{-3}	0.0049×10^{-3}	.0718
WS 899	1.323×10^{-3}	0.731×10^{-3}	0.0154×10^{-3}	.0695
BS 805	0.1589×10^{-3}	0.0114×10^{-3}	0.0005×10^{-3}	.0047
BS 1028	0.2821×10^{-3}	0.0142×10^{-3}	0.0010×10^{-3}	.0081

*ANNUAL USAGE = 25 HOURS @ CONDITION 1
+39 HOURS @ CONDITION 2
+511 HOURS @ CONDITION 3

B-52 FATIGUE DAMAGE RATE REDUCTION WITH LAMS

(FATIGUE DUE TO TURBULENCE)



IG700988-31

An analytical study was conducted during the LAMS program to define potential benefits of a LAMS FCS on the Lockheed C-5A. Data for the C-5A study was provided by Lockheed-Georgia. A system was synthesized for the longitudinal and lateral-directional axes for a representative C-5A flight condition: Mach 0.533, 292 KEAS, 10,000 feet altitude, 593,000 pounds gross weight. System definition was based on fatigue damage rate reduction and ride quality improvement in turbulence. Fatigue damage rate and ride quality during pilot maneuvering or ground-air-ground aircraft cycling were not investigated. System stability and handling qualities constraints were imposed during the analysis.

The C-5A has a conventional stability augmentation system used during normal operating conditions. Therefore, performance of the LAMS FCS was compared to performance with this conventional operational SAS referred to as the "Baseline SAS". Baseline SAS characteristics were supplied by Lockheed.

Fatigue damage rates shown in the table are computed from RMS stress and stress rates for the combined longitudinal and lateral-directional axes.

The LAMS longitudinal FCS significantly reduces fatigue damage rates due to turbulence at the two wing stations (120 and 746) and at the forward body station (1106). At the aft body station (1804) and at the horizontal tail root, the longitudinal FCS slightly increases fatigue damage rate. However, fatigue damage rate at these stations is small. Since the LAMS lateral-directional FCS is beneficial at both stations, the increase in the longitudinal axis is not significant. The longitudinal FCS has no effect on vertical tail fatigue damage rate.

The LAMS lateral-directional FCS significantly reduces fatigue damage rate at all aircraft locations investigated. At body station 1804, fatigue damage rate is reduced more than the increase from the LAMS longitudinal FCS, resulting in a net improvement. At the horizontal tail root, the lateral-directional FCS only partially cancels the fatigue damage rate increase in the longitudinal axis.

C-5A FATIGUE DAMAGE RATE REDUCTION WITH LAMS

Vehicle Stress Station	Fatigue Damage Per Hour		
	Unaugmented Aircraft	Augmented Aircraft	
		Baseline SAS	LAMS FCS
Wing Station 746	0.447×10^{-4}	0.386×10^{-4}	0.924×10^{-8}
Wing Station 120	0.100×10^{-3}	0.668×10^{-4}	0.576×10^{-9}
Body Station 1106	0.313×10^{-11}	0.105×10^{-11}	0.326×10^{-13}
Body Station 1804	0.222×10^{-6}	0.208×10^{-7}	0.224×10^{-8}
Horizontal Tail Root	0.963×10^{-9}	0.405×10^{-9}	0.491×10^{-8}
Vertical Tail Root	0.594×10^{-6}	0.635×10^{-7}	0.704×10^{-9}

IG700988-76

This chart illustrates C-5A vertical and lateral ride smoothing obtained with the LAMS SAS. A (g's/ft/sec) is defined in this and subsequent charts as RMS acceleration per unit gust.

Vertical RMS acceleration reductions with the LAMS SAS range from 22 percent at the pilot's station (fuselage station 395) to 42 percent at the aft fuselage (station 2406). The net effect of the LAMS system is to equalize RMS acceleration along the fuselage. Acceleration levels can be reduced further, but only at the expense of loss in fatigue damage rate reduction.

The existing C-5A spoilers provide most of the LAMS vertical control by controlling rigid body motions through direct lift. RMS spoiler deflection is 0.55 deg/ft/sec of gust, compared to 0.093 and 0.028 deg/ft/sec for the aileron and elevator, respectively.

Lateral RMS acceleration reductions with the LAMS SAS range from 27 percent at the cg to 53 percent at the aft fuselage. At the pilot's station lateral accelerations are reduced 33 percent. As in the longitudinal axis, the net effect of the LAMS FCS is to equalize lateral accelerations along the fuselage.

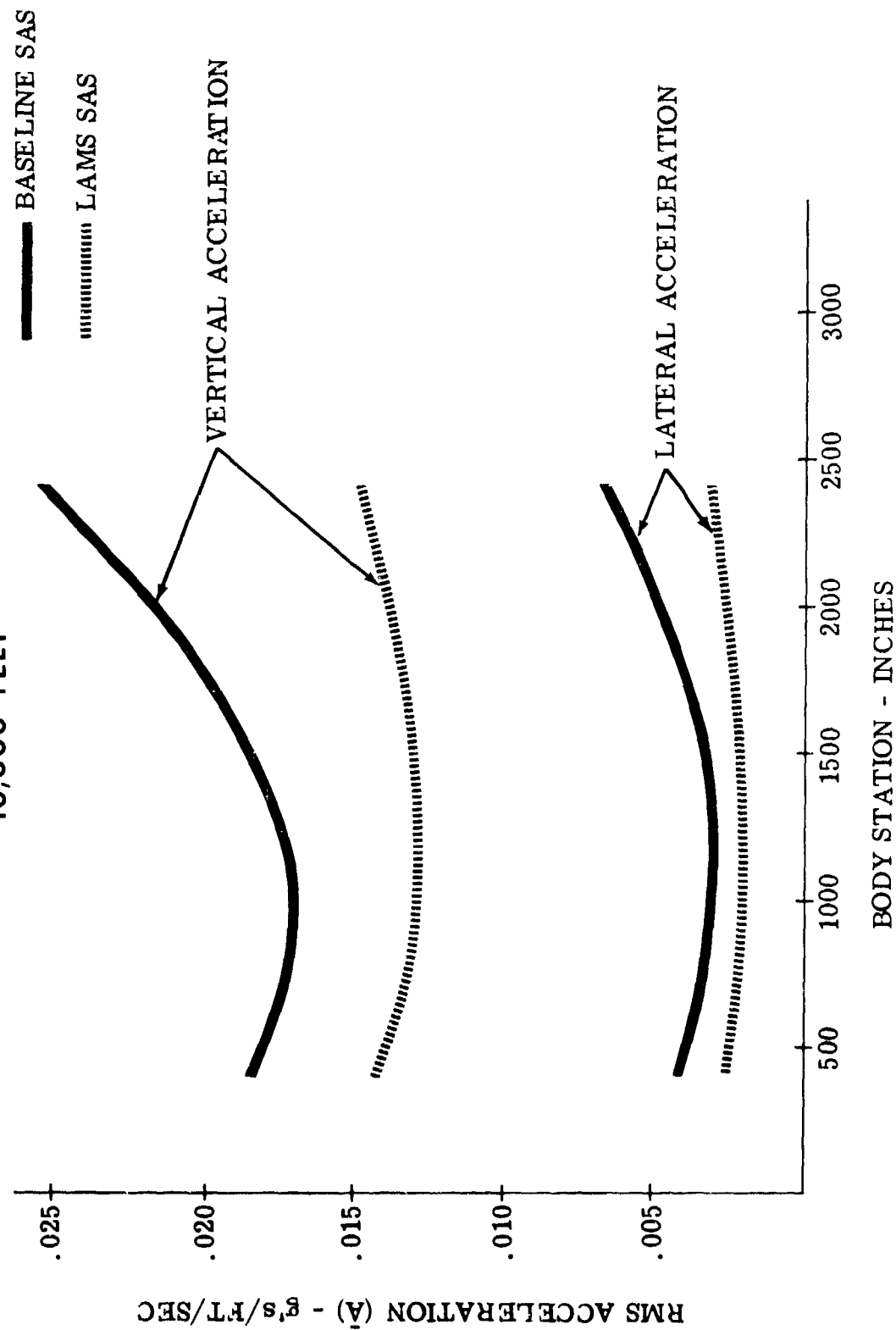
The existing C-5A lower rudder provides most of the LAMS control in the lateral-directional axis. RMS rudder deflection is 0.20 deg/ft/sec of gust compared to an aileron deflection of 0.0069 deg/ft/sec.

C-5A RIDE SMOOTHING WITH LAMS SAS

593,000 POUNDS

292 KEAS

10,000 FEET



AEROELASTIC MODELING

(References 34-41)

Wind tunnel testing of dynamically scaled models is economically desirable early in the design stage of modern aircraft to provide accurate predictions of airplane dynamic characteristics prior to flight test. Boeing aeroelastic modeling research and development is directed toward verifying model dynamic accuracy and broadening aeroelastic modeling technology to include advanced control systems.

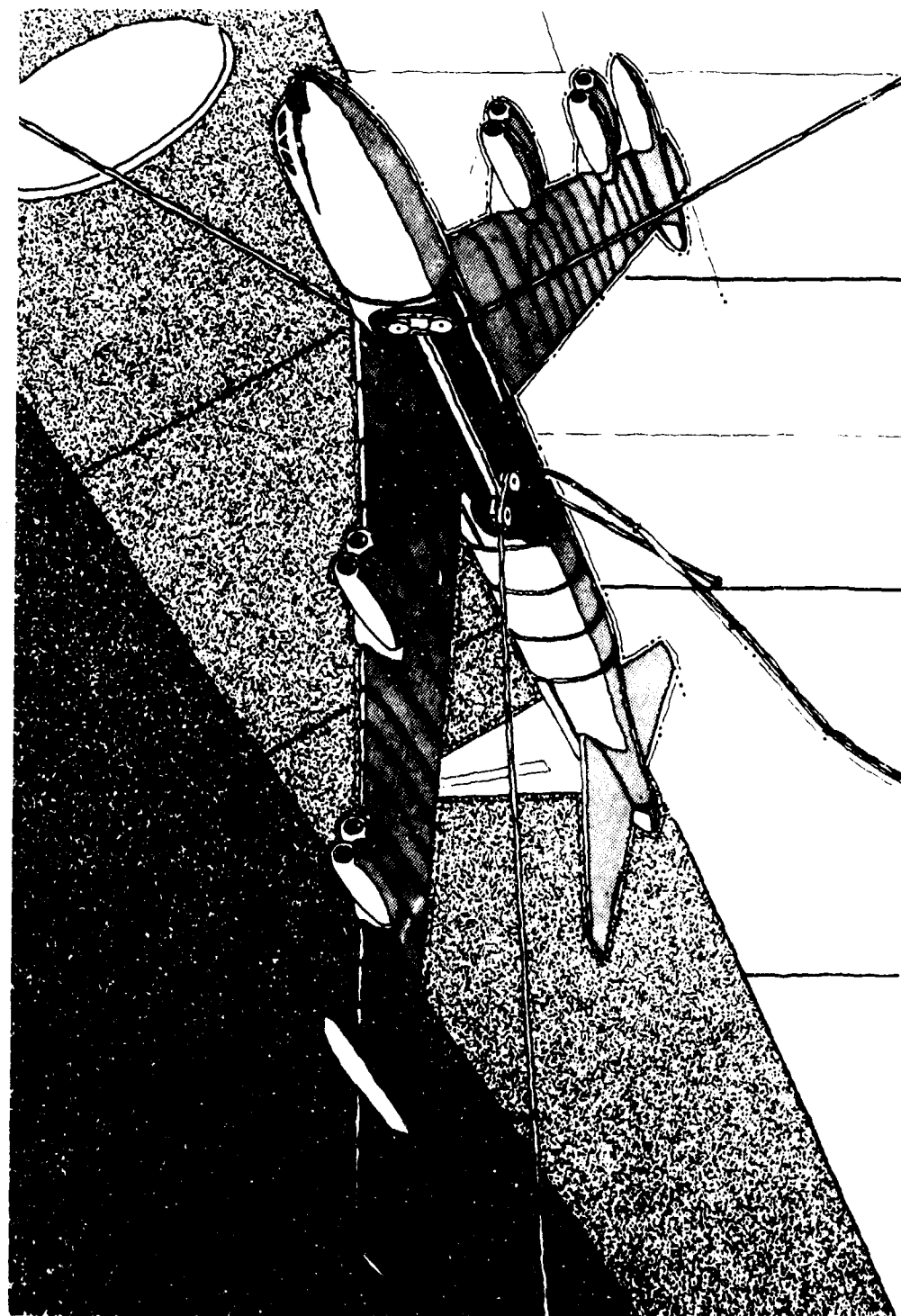
Boeing-Wichita assisted NASA Langley Research Center in developing a one-thirtieth scale flexible model of a B-52E airplane at a gross weight of 419,000 pounds. The model was developed for dynamic response testing in the Langley Transonic Dynamics Tunnel using an airstream oscillator located in the tunnel. The model contained electrically powered wide bandpass elevator and aileron control surfaces for active mode suppression evaluations. The control systems will have a 25 Hz bandwidth and minimum nonlinearity at low amplitudes.

Breadboard mechanization and testing have identified control system mechanizations that achieve desired performance.

A model ride control system is being synthesized to reduce RMS vertical accelerations along the fuselage. Canards and inboard flaperons will be installed for ride smoothing control surfaces.

Boeing is also assisting NASA Langley in developing a one-seventeenth scale SST wing model for evaluating and demonstrating a flutter suppression control system.

AEROELASTIC MODEL WIND TUNNEL TESTS



SST

(References 42-49)

Analytical and simulation studies were initiated in 1967 to determine potential benefits of a LAMS SAS on SST variable sweep and fixed wing configurations. SAS configurations were evaluated for performance improvements in three areas: controllability, ride smoothing and flutter.

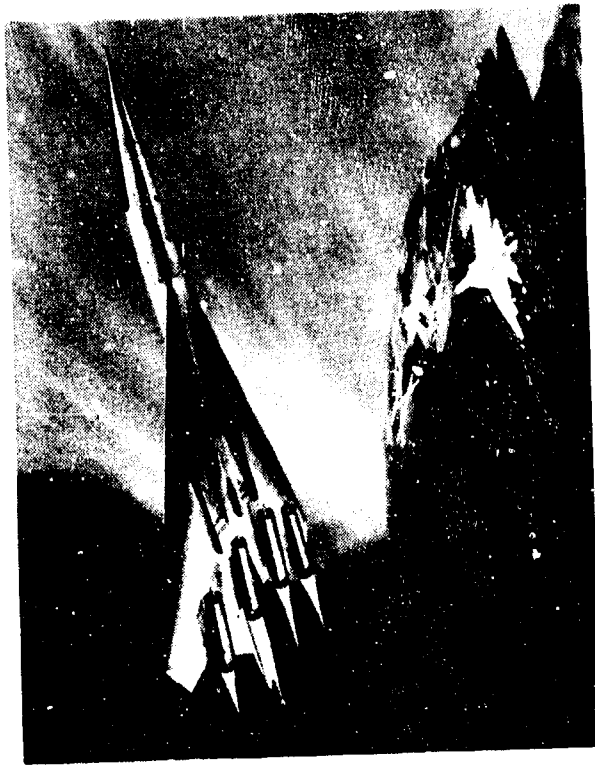
Aircraft controllability during heavy turbulence was analyzed using a Northrop-Norair large-amplitude moving base simulator. SST and 727-200 controllability characteristics in the same turbulent environment were compared and improvements provided by a LAMS SAS were evaluated.

Passenger ride quality analyses and tests were conducted with and without a LAMS SAS to develop passenger ride quality criteria, to develop a ride quality analysis method and to evaluate SST ride qualities. Passenger sensitivities to accelerations at frequencies typical of large commercial aircraft were determined from moving base simulator tests. Tests conducted at discrete mission points compared SST ride qualities to those of existing aircraft. A method was developed for analytically evaluating passenger ride qualities based on a mission profile approach. The method employs power spectral density analysis techniques and considers flexible aircraft response to disturbances in vertical and lateral axes.

An analytical study was conducted to determine the feasibility of employing a SAS to increase SST flutter speed and to identify potential SAS concepts. The study indicated that a flutter SAS is feasible. However, such a system is not being incorporated on the SST since it has not been flight demonstrated.

SST ANALYTICAL STUDIES

- CONTROLLABILITY
- RIDE SMOOTHING
- FLUTTER MODE CONTROL



VARIABLE SWEEP CONFIGURATION



FIXED WING CONFIGURATION

IG700988-11

Analytical studies conducted on the SST defined potential benefits of ride smoothing SAS concepts. SAS variables considered during the study included control surfaces, sensors, signal shaping and actuator requirements.

The first four body modes in the vertical plane covering a frequency range from approximately 1.4 to 3.8 Hz, contribute significantly to gust induced accelerations. The ride smoothing SAS concepts were designed to suppress these elastic vibration modes without significantly affecting rigid body dynamics.

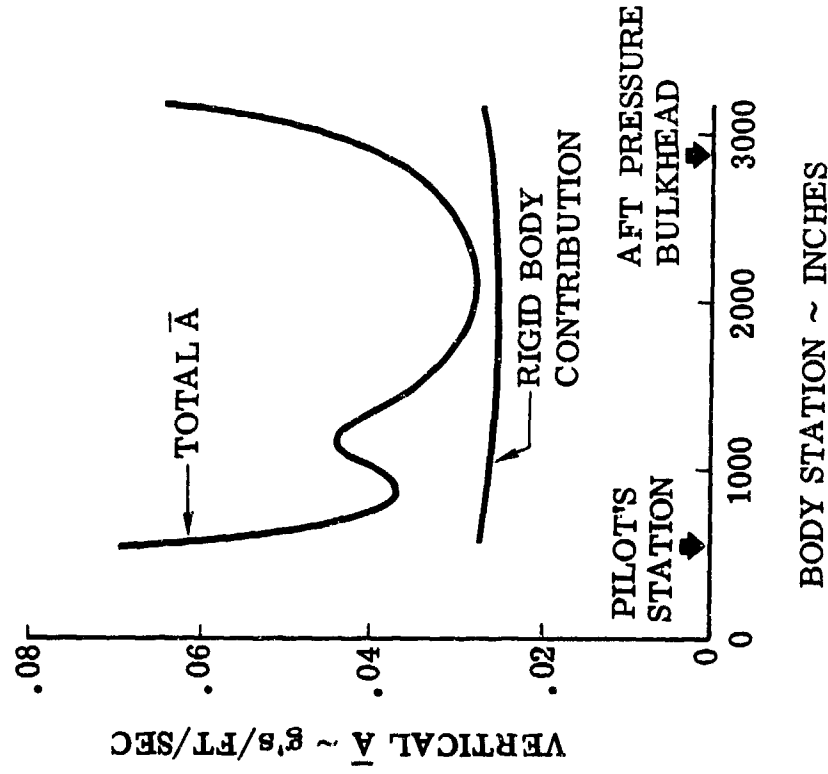
This chart illustrates fuselage vertical accelerations for a subsonic descent condition with and without a ride smoothing SAS. The upper curves are total vertical accelerations, the lower curves are rigid body contributions, and the differences between the curves are the contributions from aircraft flexible modes.

With the ride smoothing SAS vertical accelerations are significantly reduced at the forward and aft ends of the aircraft where the acceleration levels are largest.

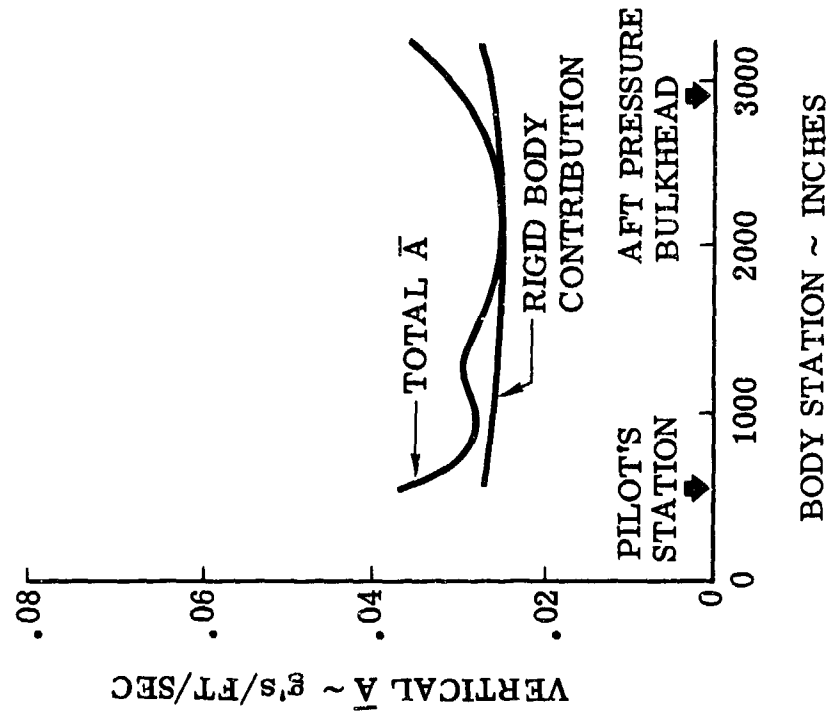
SST VERTICAL RIDE SMOOTHING WITH SAS

SUBSONIC DESCENT

WITHOUT SAS



WITH RIDE SMOOTHING SAS



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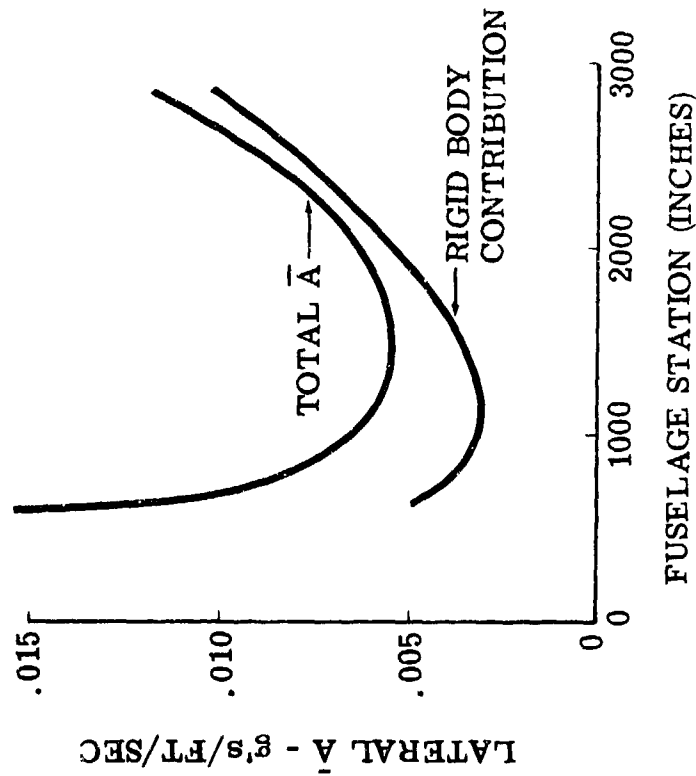
In the lateral-directional axis the SST first body bending mode, with a frequency of approximately 1.5 cps, is the only elastic mode that contributes significantly to antisymmetric vibrations in turbulence.

This chart shows RMS accelerations with and without the ride smoothing SAS for a subsonic descent flight condition. The SAS suppresses the first mode at all fuselage stations, particularly along the forward portion of the fuselage.

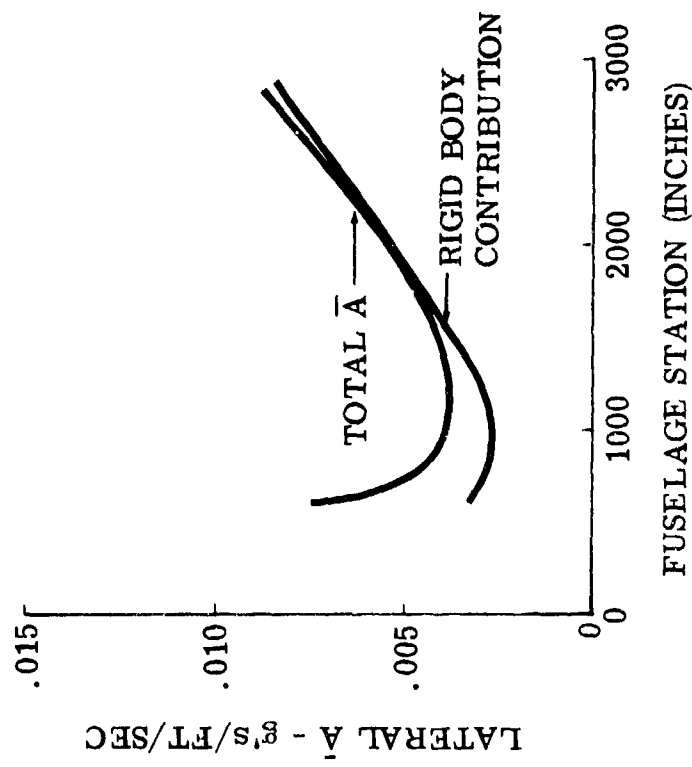
SST LATERAL RIDE SMOOTHING WITH SAS

SUBSONIC DESCENT

WITHOUT SAS



WITH RIDE SMOOTHING SAS



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Flutter analyses conducted on an SST strength designed configuration revealed a wing mode and a body-wing mode with zero damping at speeds less than $1.2 V_{DIVE}$, requiring over 10,000 pounds of additional structure to provide an adequate flutter margin. The condition occurred at Mach 0.90 and a gross weight of 395,000 pounds. Studies were conducted to determine the feasibility of damping these modes with a SAS to eliminate this additional weight.

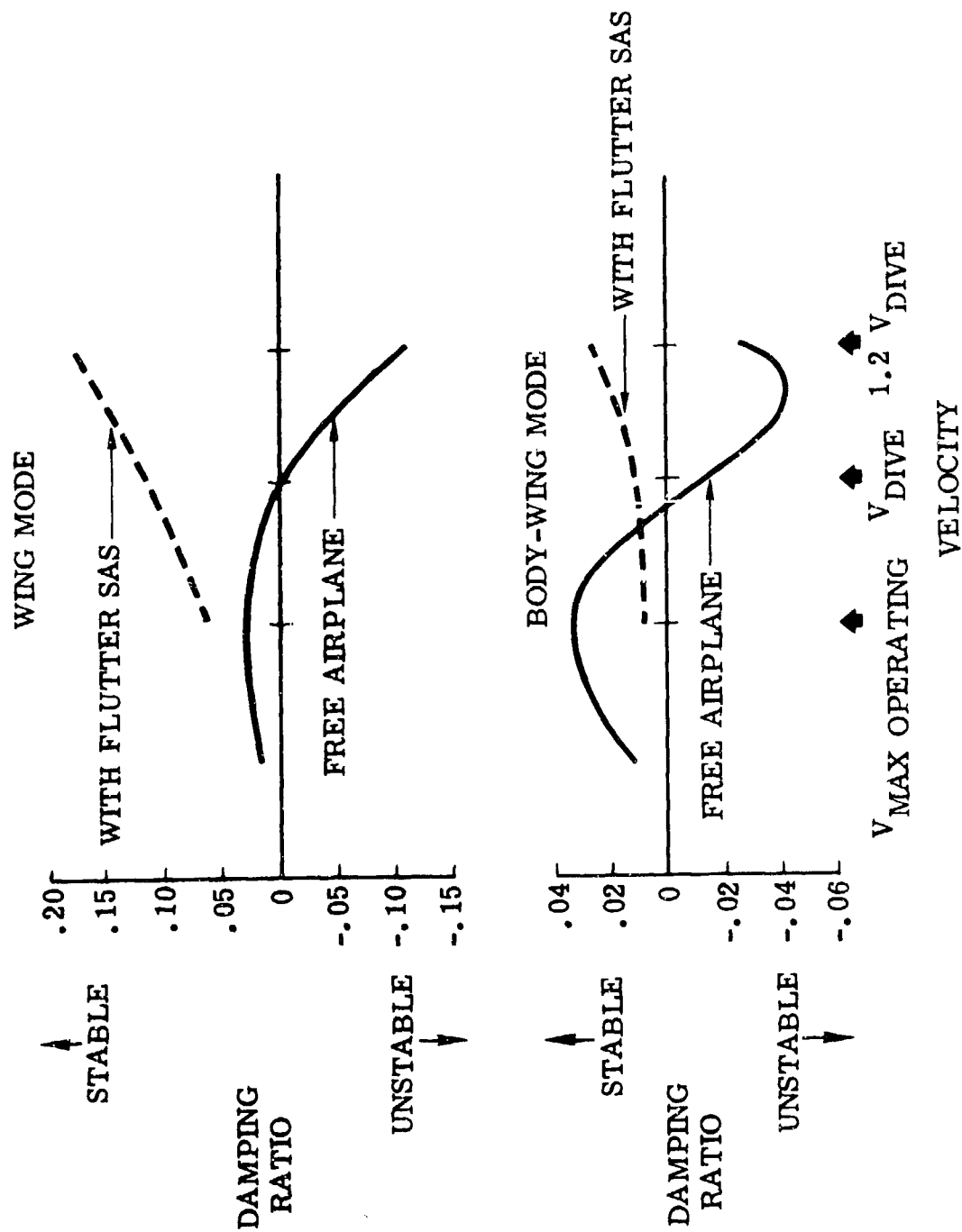
The studies focused on identifying particular SAS control surfaces, sensed signals, and signal shaping that stabilized all airplane modes between 0.96 and $1.2 V_{DIVE}$. A major portion of the study was devoted to identifying control surface types and locations that offered the most potential for stabilizing the two flutter modes, including both single and multiple control surface concepts. A single wing tip aileron, used with wing mounted sensors, provided the most feasible SAS concept.

This chart illustrates damping ratios of the two flutter modes, with and without the aileron SAS, as a function of velocity. Without the SAS the airplane becomes unstable at $0.96 V_{DIVE}$. The SAS extends the flutter condition of both modes beyond $1.2 V_{DIVE}$. The chart on the next page illustrates the flutter condition on a root locus as a function of speed.

SST FLUTTER MODE CONTROL

MACH 0.90

395,000 POUNDS

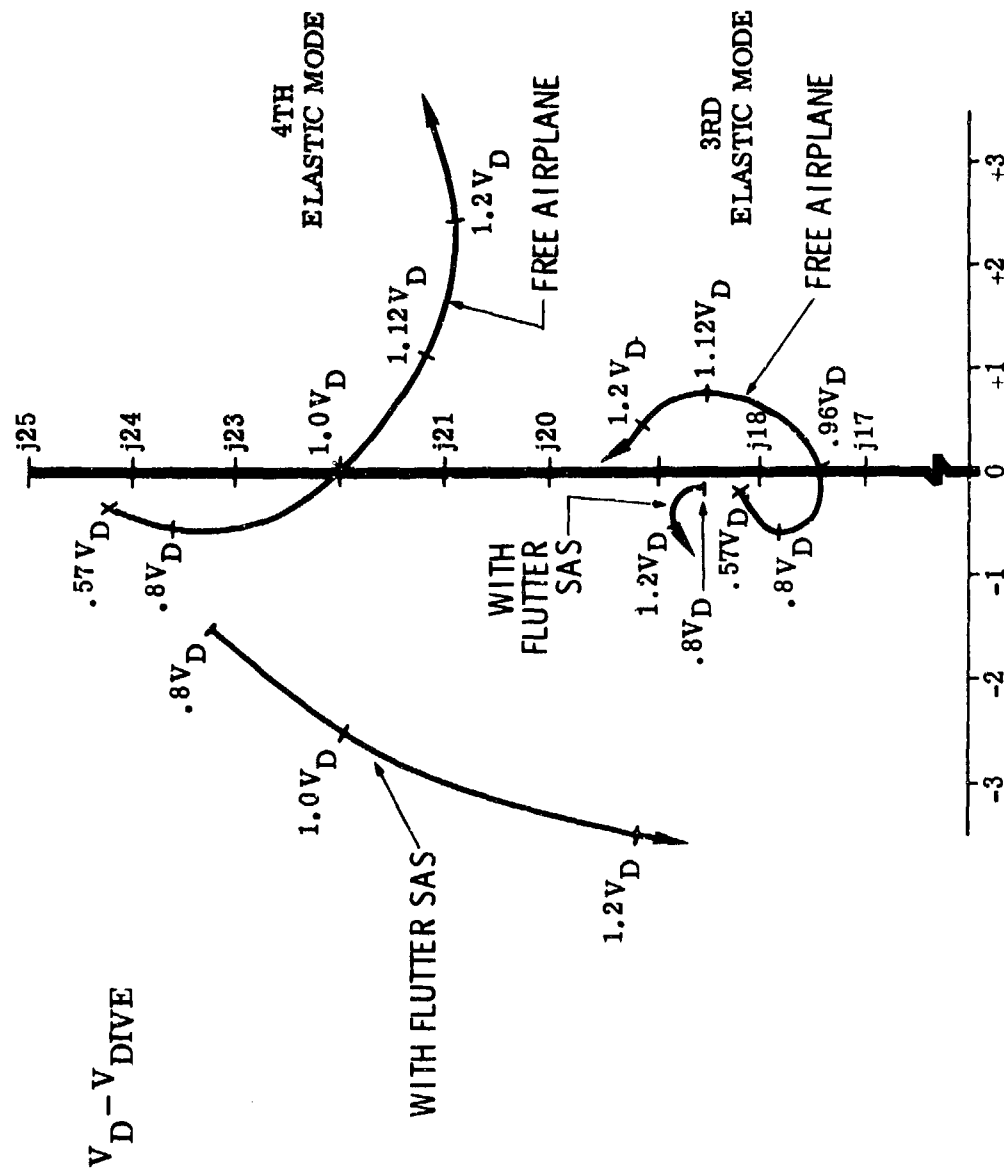


This figure illustrates the root locus of the two SST flutter modes, as a function of velocity. Free airplane neutral stability is encountered when the third elastic mode (body-wing mode) crosses the imaginary axis at $0.96 V_{DIVE}$. As speed is increased further, the fourth elastic mode (wing mode) becomes unstable at $1.0 V_{DIVE}$.

The flutter SAS employs wing tip aileron surfaces and two wing mounted pitch rate gyros to control the two flutter modes. Gyro signals are shaped with a lead-lag filter, and SAS feedback gain is varied as a function of altitude.

SST ROOT LOCUS WITH FLUTTER SAS

MACH 0.90
395,000 POUNDS



STOL

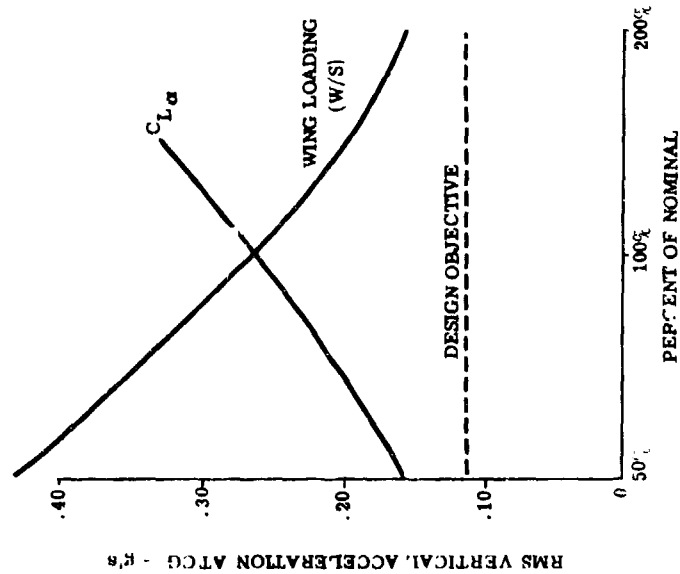
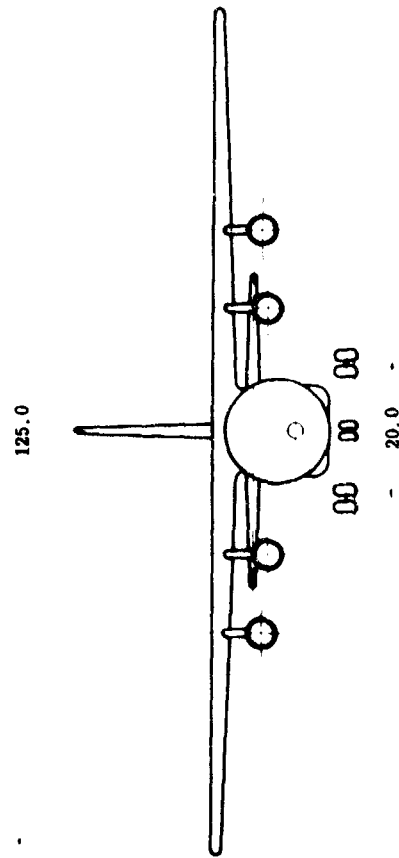
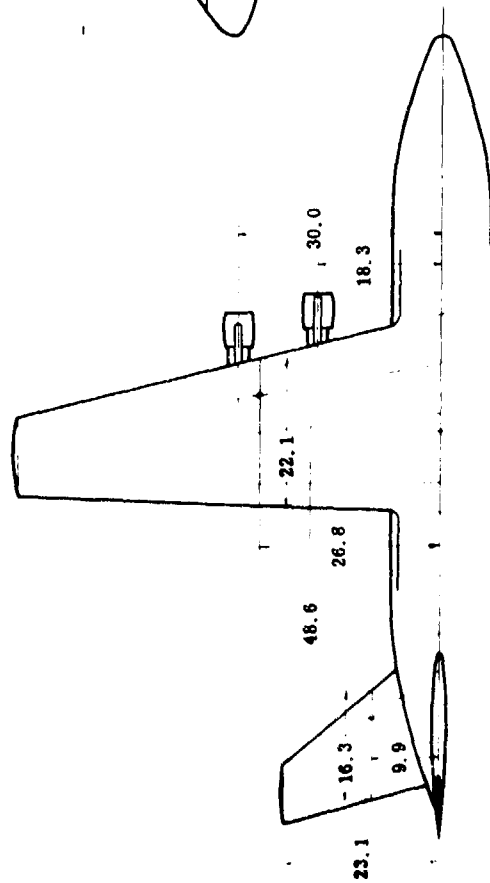
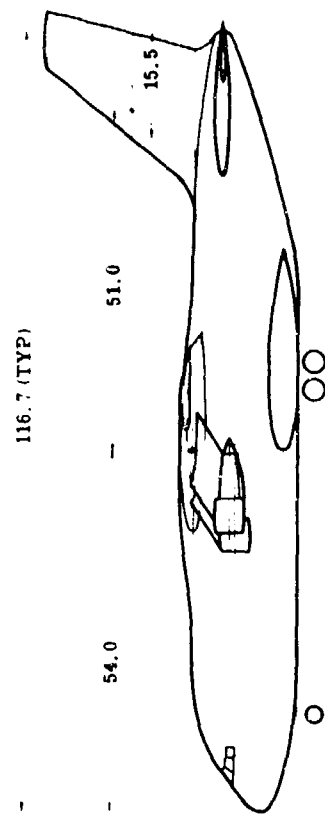
A contract was initiated in October 1970 with NASA Langley Research Center to conduct a preliminary design study of a commercial STOL airplane incorporating an advanced control system. The objective is to explore the potential of modern controls technology for providing satisfactory ride qualities and high speed cruise performance for a high lift, low wing loading STOL aircraft design. The potential advantages of a low wing loading STOL transport, including simplicity, reliability and low noise, make it desirable to examine this class of aircraft in relation to other design approaches. The study includes factors normally considered in the preliminary design of an aircraft, including basic configuration development, performance, propulsion, structure, loads, stability and control, handling qualities, noise and weights, with emphasis on improved ride qualities provided by a SAS.

The airplane is being designed for 130 passengers, 2000 feet field length, cruise Mach number of 0.80 and a range of 750 nautical miles.

Airplane and control system performance are being evaluated at three flight conditions: cruise, high speed descent (which normally presents the most severe ride) and landing approach.

The lower right graph illustrates parametric trades of the effects of wing loading and lift curve slope on vertical acceleration at the high speed descent condition, with other parameters constant. The configuration is being designed for a wing loading of 50 pounds per square foot and a CL_{α} of 6.65 per radian (at the high speed descent condition), giving a free airplane rigid body cg vertical acceleration of 0.282 RMS g's. Based on results of recent moving base simulator ride quality tests, a design objective of 0.11 RMS g's maximum was established for this condition. To meet this design objective without a ride smoothing SAS, wing loading must be significantly increased or CL_{α} significantly reduced. As shown on the next chart, a ride smoothing SAS accomplishes this objective without a reduction in CL_{α} or an increase in wing loading.

LOW WING LOADING STOL DIMENSIONS IN FEET



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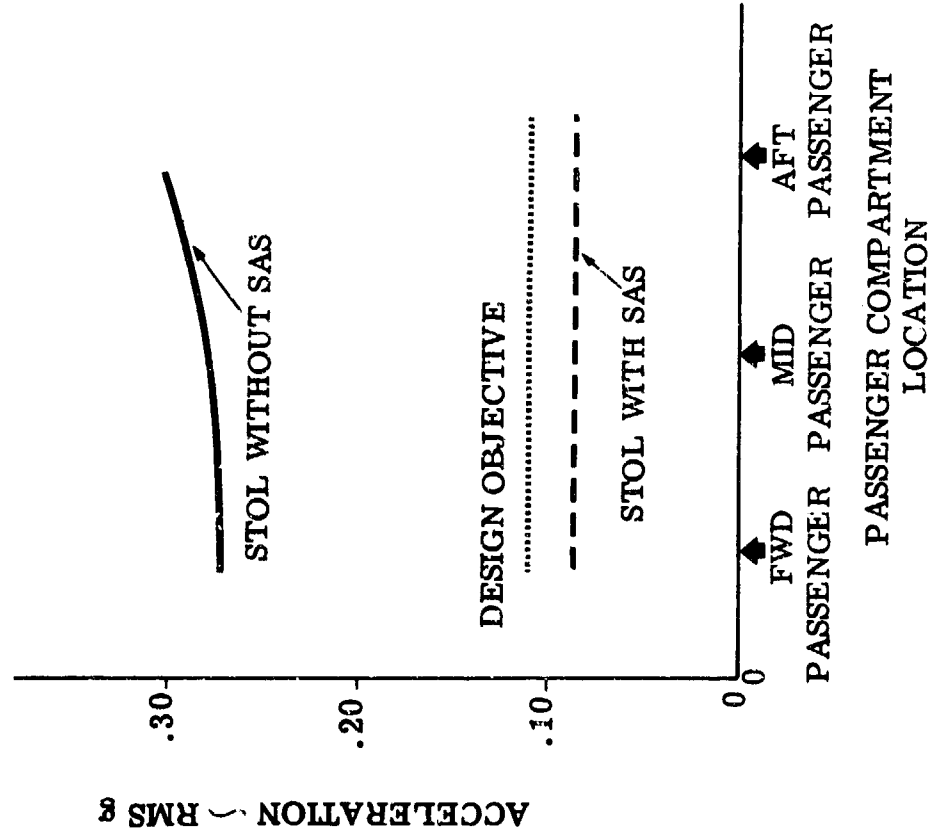
Gust alleviation is provided by a ride smoothing SAS employing sensors located along the fuselage. Wing and horizontal tail trailing edge control surfaces reduce vertical accelerations, and the rudder reduces lateral accelerations.

The vertical and lateral acceleration design objectives of 0.11 and 0.055 RMS g's are based on acceptable acceleration levels established during limited ride quality moving base simulator tests. These tests indicated that humans are approximately twice as sensitive to lateral oscillations as vertical oscillations at rigid body frequencies. Therefore, the lateral acceleration design objective was set at one-half the vertical acceleration design objective. Because of this factor-of-two human sensitivity phenomenon, the lateral acceleration scale is one-half the vertical acceleration scale to facilitate comparisons of vertical and lateral ride qualities.

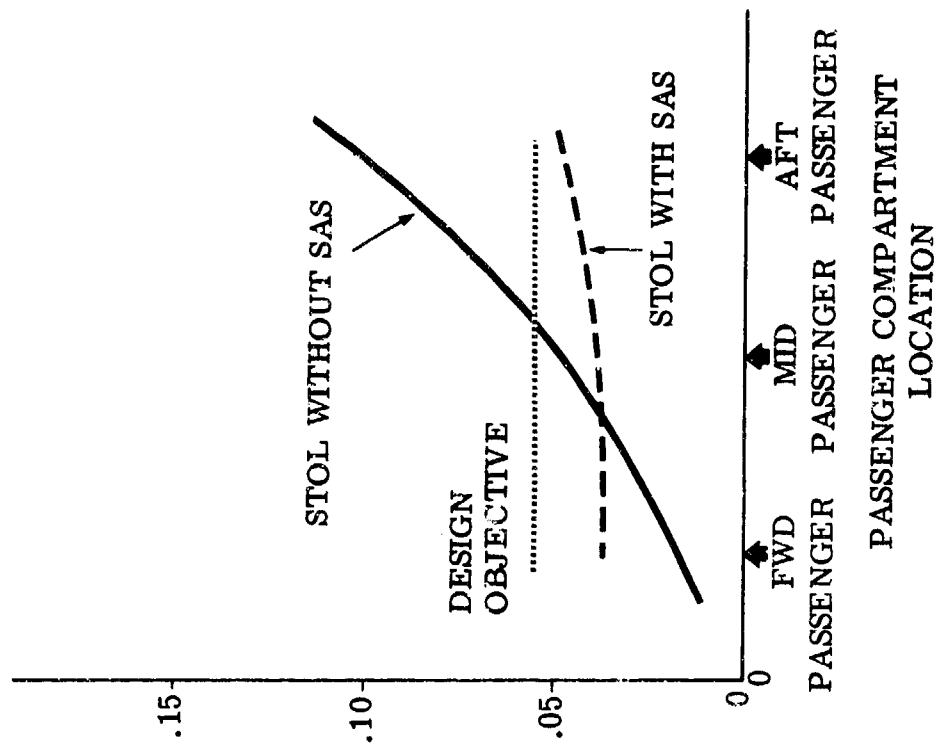
STOL RIDE SMOOTHING WITH SAS

LOW WEIGHT, HIGH SPEED DESCENT CONDITION

VERTICAL



LATERAL



CCV

(References 50-55)

Boeing-Wichita submitted a Controls Configured Vehicles (CCV) proposal to the Air Force Flight Dynamics Laboratory in May 1969 for a program designed to demonstrate significant improvements in weapon system performance through application of advanced controls concepts during the preliminary design phase of an airplane. The program is expected to begin in early 1971 and includes flight control system development and validation of the four advanced control concepts listed on the opposite page.

The remaining pages of this document discuss feasibility studies conducted for these four concepts, potential benefits, and planned flight validations on the LAMS airplane.

CONTROLS CONFIGURED VEHICLE PROGRAM

- FLUTTER CONTROL
- RIDE SMOOTHING
- MANEUVER LOAD CONTROL
- AUGMENTED STABILITY

FLUTTER CONTROL

Recent airframe design trends show a steady increase in flexibility, slenderness ratio, and maximum operating speeds. These trends increase the likelihood of an airframe design exhibiting flutter within the aircraft operating envelope. The flutter phenomenon occurs when aeroelastic structural mode damping reduces to zero.

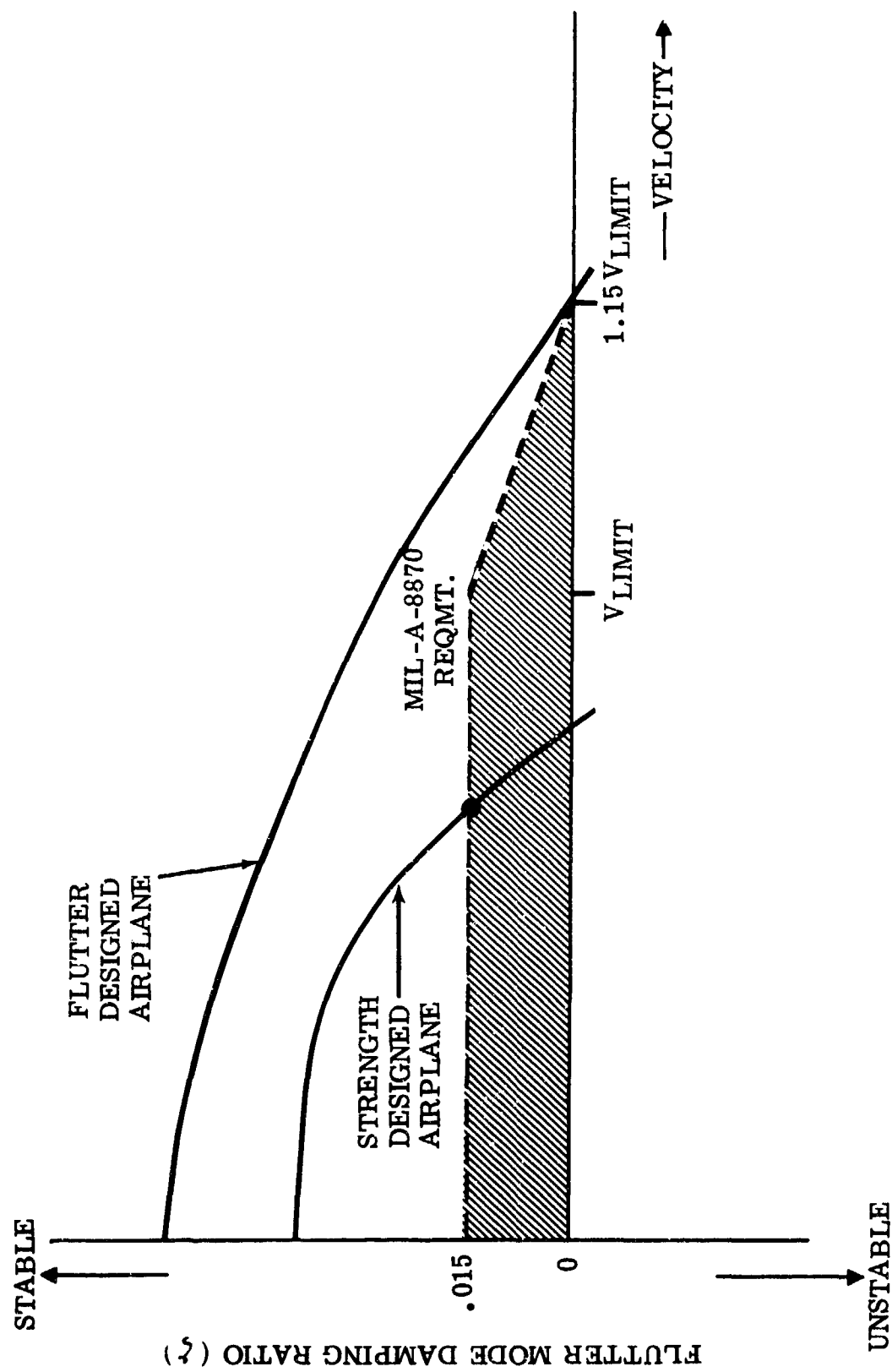
Contemporary airframe design practices generally start with an airframe structural design based on strength requirements. An aircraft thus designed meets strength criteria but has insufficient stiffness to meet flutter requirements. Aircraft exhibiting this characteristic include the SST, B-1, B-52 and others. The flutter problem is further compounded when extended to tactical aircraft having a wide variation of external stores. Additional complexities are encountered when an aircraft has a variable geometry design, inducing aerodynamic coupling between the empennage and wing.

Presently flutter problems are solved by modifying the structure, adding mass balance and/or establishing suitable flutter placards. These approaches are generally time consuming, involve weight penalties, and restrict weapon systems to specific missions in some instances.

This chart compares requirements of MIL-A-8870 for 0.015 damping at V_{LIMIT} and positive damping up to 1.15 V_{LIMIT} to typical strength designed and flutter designed airplane damping trends.

An Active Flutter Suppression System offers the potential for solving some flutter problems with significantly less weight.

FLUTTER CONTROL POTENTIAL BENEFIT



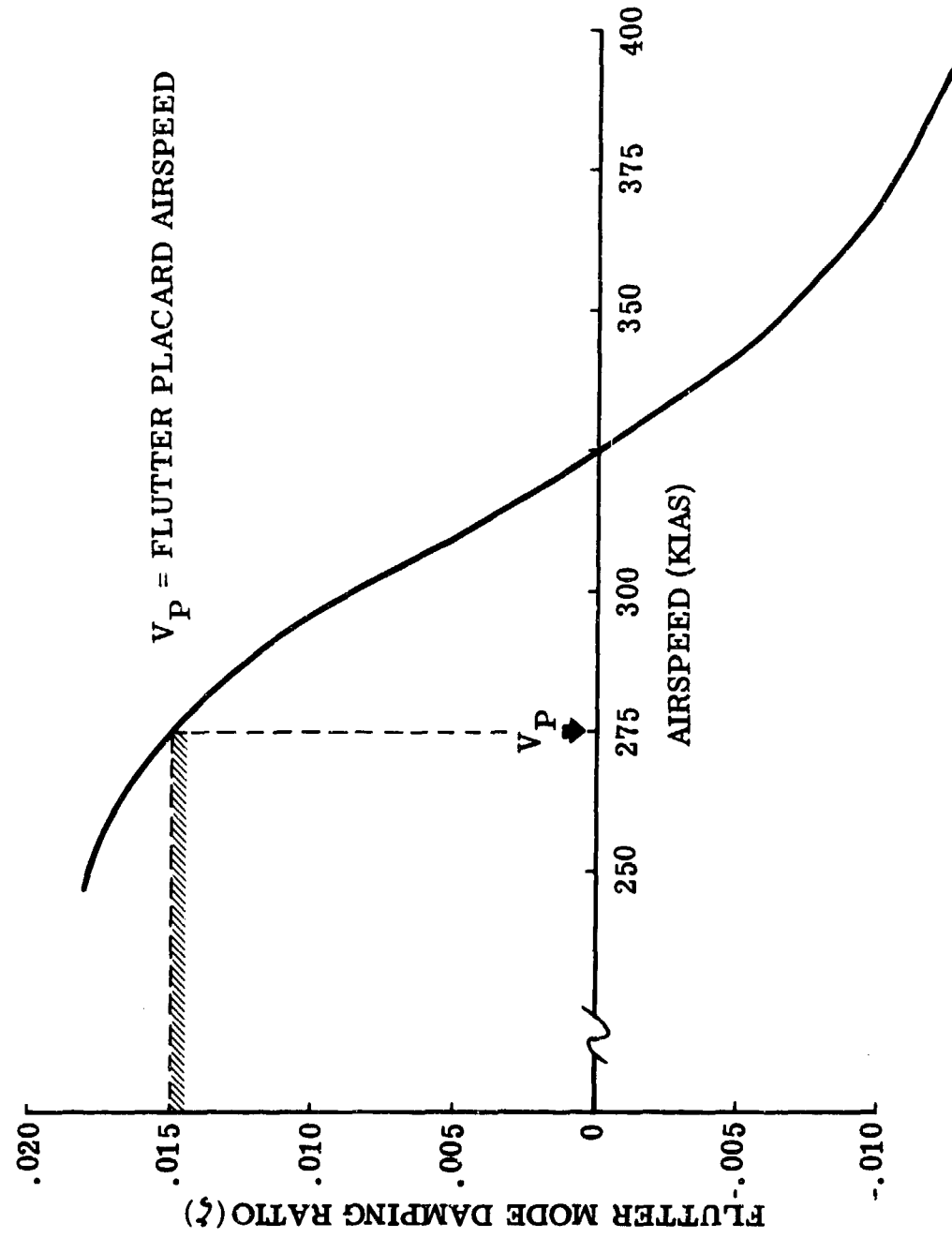
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A study is being conducted to define preliminary concepts for flight demonstrating active flutter control during the CCV program using the LAMS test airplane. The work is being sponsored by the Air Force Flight Dynamics Laboratory.

The LAMS test vehicle was selected for the flight demonstration, since adverse ballast in the external wing tanks makes the airplane flutter at 325 KIAS at an altitude of 21,000 feet and 280,000 pounds gross weight.

This chart shows the predicted damping ratio versus airspeed for the 2.4 cps flutter mode. At 275 KIAS the flutter mode damping ratio reduces to less than the design requirement of 0.015, thus establishing the airplane placard airspeed (V_p).

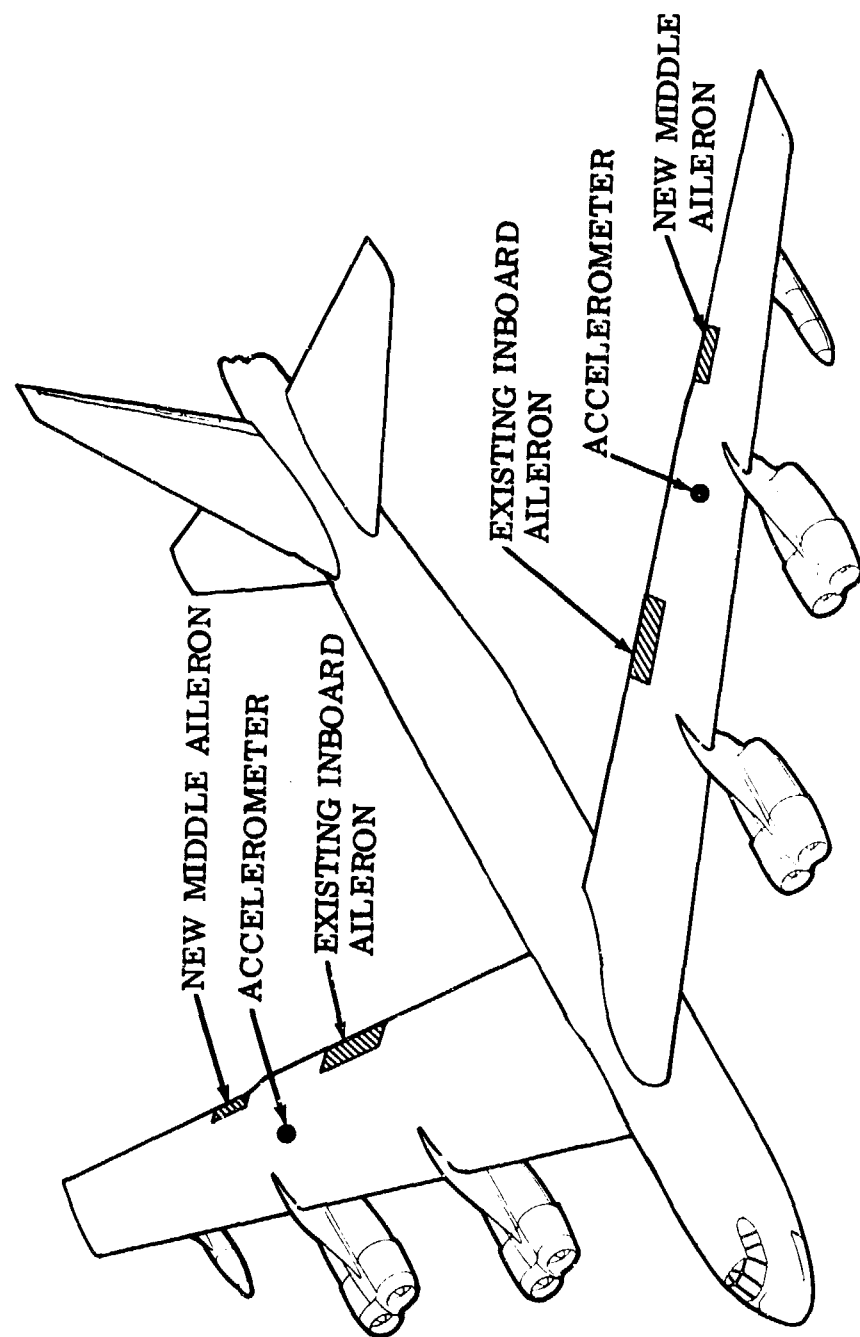
FLUTTER CONTROL FLIGHT DEMONSTRATION



The CCV flutter SAS study has identified airplane control surfaces and associated sensors and feedback shaping networks that exhibit the most flutter control potential. Two flutter SAS configurations were defined using the existing inboard aileron and a combination of the existing inboard and a new middle ailerons.

This chart illustrates the relative locations of the two ailerons. An accelerometer located in each wing controls the single surface and dual surface configurations. Bandpass filters are used in both configurations to attenuate feedback signals outside the 1 to 4 cps frequency range.

FLUTTER SAS CONFIGURATION



Math model and system parameters were varied to define the sensitivity of flutter SAS configurations under adverse conditions. This chart shows augmented flutter mode damping versus airspeed for the single and dual aileron configurations under nominal conditions and with the most adverse parameter variations anticipated.

Under nominal conditions the single aileron flutter SAS increases placard speed over 40 percent. With the most adverse parameter variation, flutter placard speed is extended 29 percent.

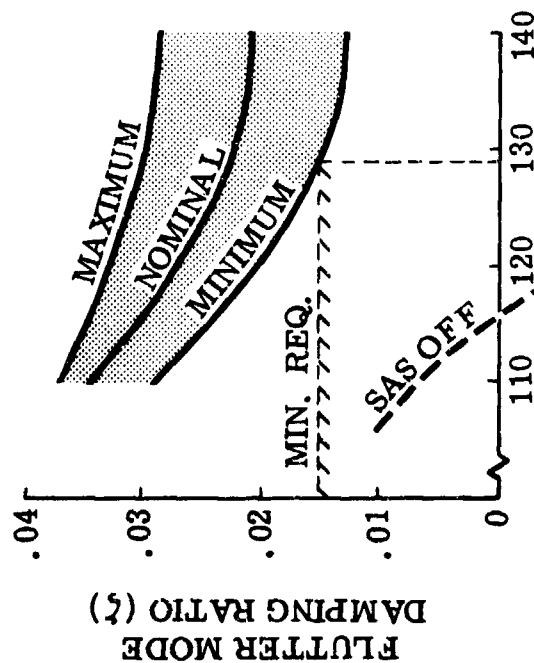
The dual aileron system provides an additional margin of control over the flutter mode and extends placard speed over 40 percent with the most adverse parameter variation.

FLUTTER SAS SENSITIVITY

21,000 FEET

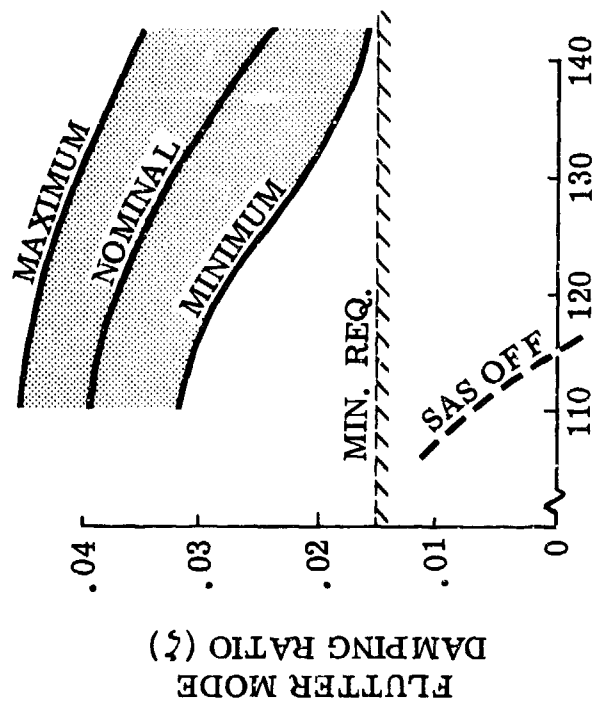
280,000 POUNDS

SINGLE AILERON SYSTEM



AIRSPEED - PERCENT OF SAS
OFF PLACARD AIRSPEED

DUAL AILERON SYSTEM



AIRSPEED - PERCENT OF SAS
OFF PLACARD AIRSPEED

RIDE SMOOTHING

A study was conducted to determine the benefits available from a ride smoothing stability augmentation system on the B-52 using various control surfaces. The study was conducted for a low level B-52E configuration at 2,000 feet altitude, 400 knots, with a gross weight of 220,000 pounds.

This chart illustrates the effectiveness of single and dual surface concepts in reducing vertical accelerations.

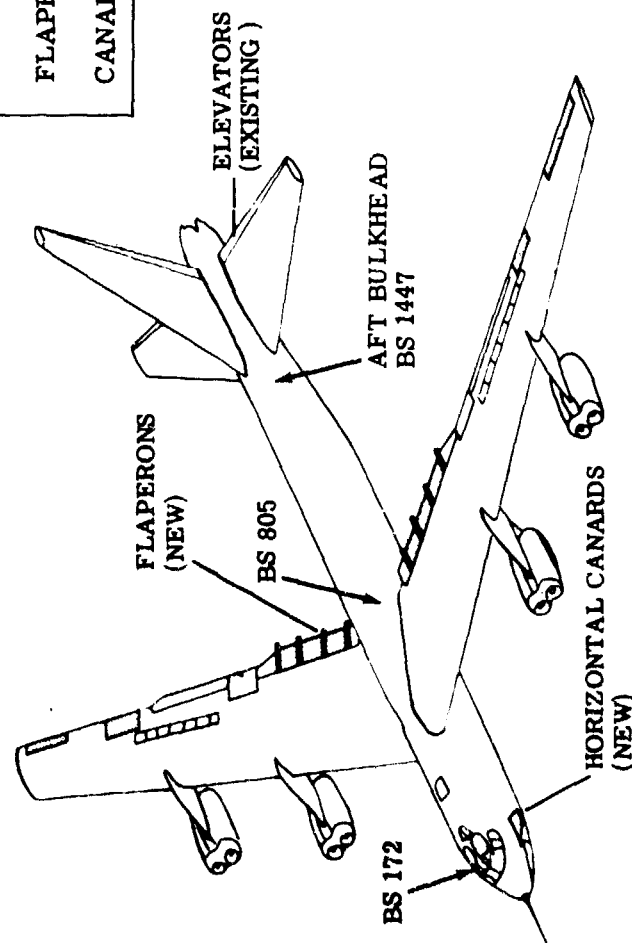
Vertical accelerations at the crew compartments (BS 172) are reduced 40 percent with a canard surface; however, aft body accelerations are increased 5 percent.

A flaperon located near the cg reduces aft body accelerations 23 percent, whereas, an elevator reduces aft body accelerations only 17 percent.

A combined canard/flaperon system shows the most potential for reducing accelerations along the entire fuselage. The next chart illustrates the reduction in vertical acceleration along the fuselage with a canard/flaperon system.

RIDE SMOOTHING POTENTIAL BENEFIT

VERTICAL ACCELERATION REDUCTIONS ~ PERCENT			
SURFACE	BS 172	BS 805	BS 1447
CANARD ONLY	40	14	5 INCREASE
ELEVATOR ONLY	7	11	17
CANARD & ELEVATOR	33	11	14
FLAPERONS ONLY	0	34	23
CANARD & FLAPERONS	39	41	19

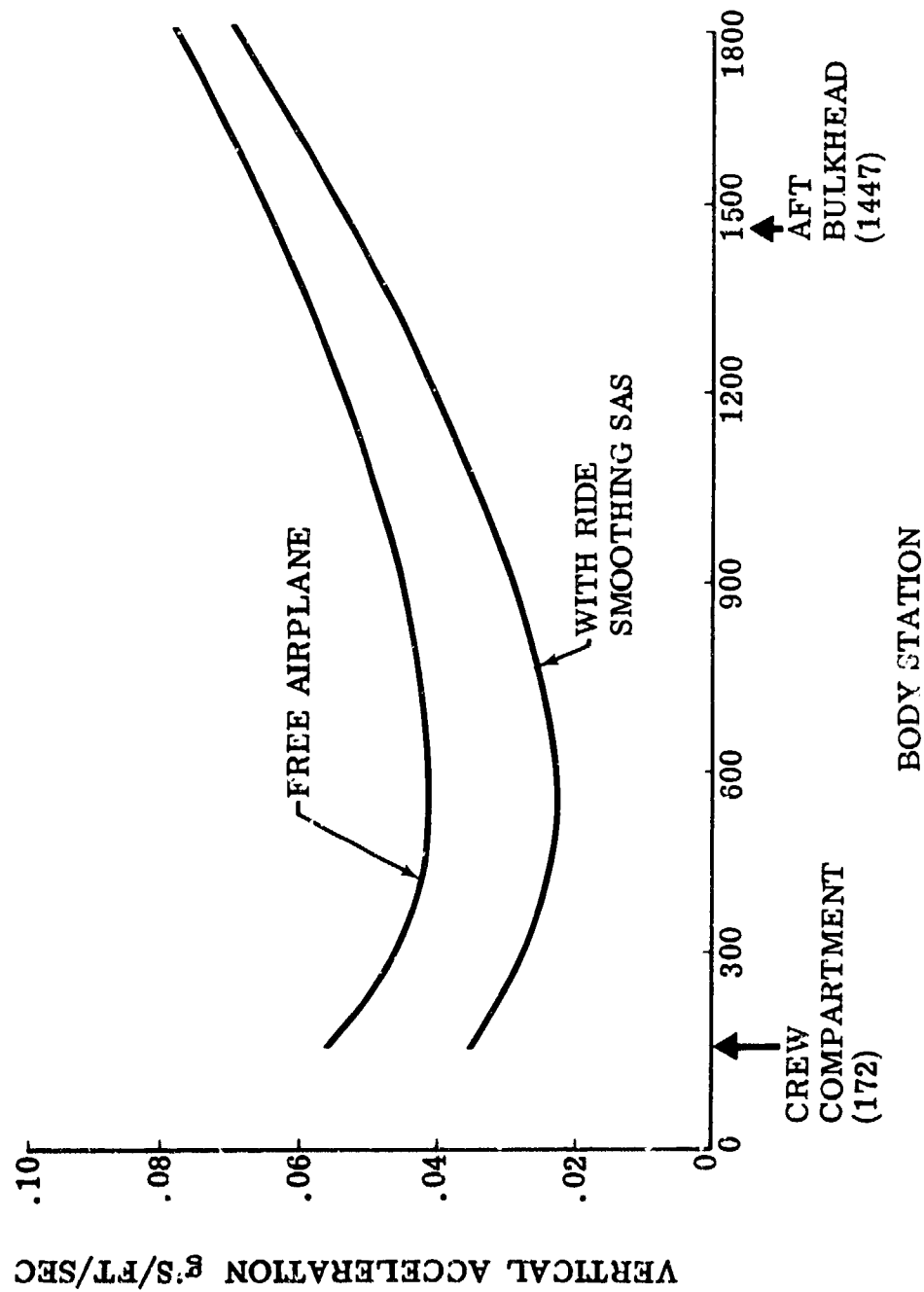


This chart illustrates the reduction in vertical acceleration along the fuselage with a canard/flaperon SAS. The canard is located at BS 172 near the crew compartment and has an area of 10 square feet per side. An accelerometer is also located at BS 172 for feedback of forward body bending mode signals to the canard. The flaperon located on the inboard portion of each wing has an area of 64 square feet. This surface functions as a gust alleviation surface and reduces gust responses in the 0 to 1 cps frequency range. The combined canard/flaperon system reduces vertical acceleration at the pilot's station from .057 to .035 g's/fps and from .062 to .050 g's/fps at the aft bulkhead.

The next chart illustrates vertical acceleration rigid body and structural flexibility components with and without the SAS.

B-52 RIDE SMOOTHING WITH CANARD/FLAPERON SAS

400 KEAS
2,000 FEET
222,000 POUNDS

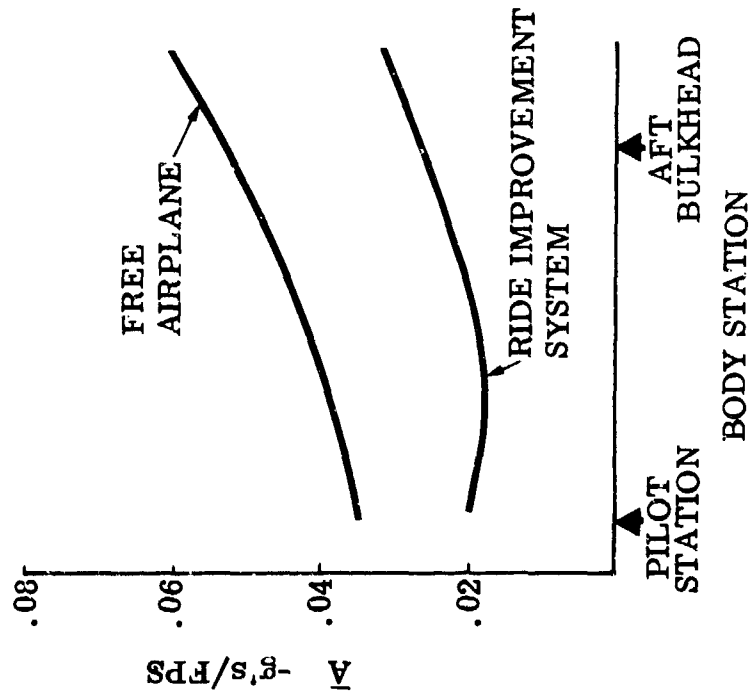


This chart illustrates B-52 rigid body and structural flexibility vertical acceleration components along the fuselage. The ride smoothing SAS reduces rigid body contributions along the entire fuselage. Structural flexibility contributions are reduced at the crew station but are increased in the aft fuselage.

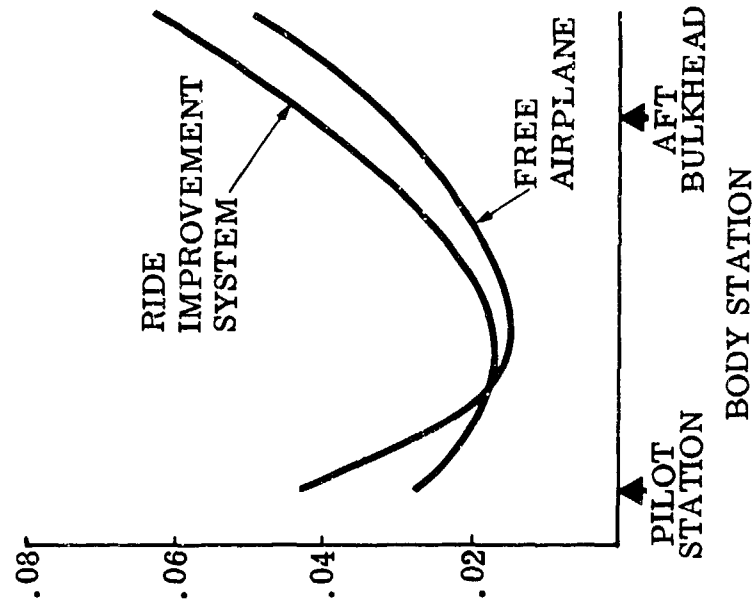
B-52 VERTICAL ACCELERATION COMPONENTS WITH CANARD/FLAPERON RIDE SMOOTHING SAS

GW - 222,000 POUNDS
ALT - 2,000 FEET
VEL - 400 KEAS

RIGID BODY CONTRIBUTION



STRUCTURAL FLEXIBILITY
CONTRIBUTION

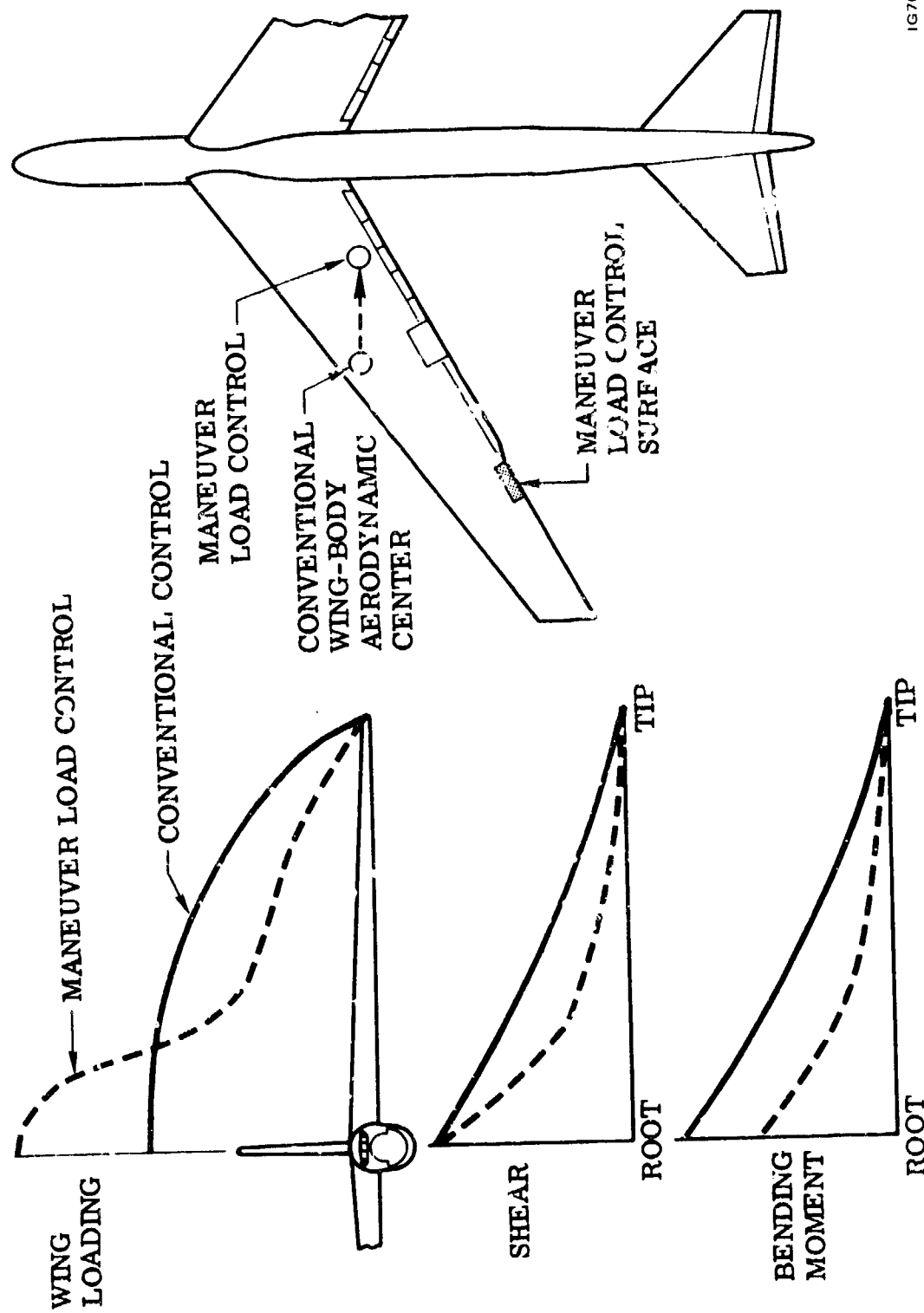


MANEUVER LOAD CONTROL

Studies have been conducted to evaluate benefits available with maneuver load control by deflecting wing control surfaces symmetrically in response to load factor commands. The wing control action moves the wing lift inboard of the conventional aerodynamic center and results in reduced wing root bending moments without increased body or tail loads.

The reduced wing loading can result in a lighter wing or increased payload with the same load factor capability.

MANEUVER LOAD CONTROL POTENTIAL BENEFIT



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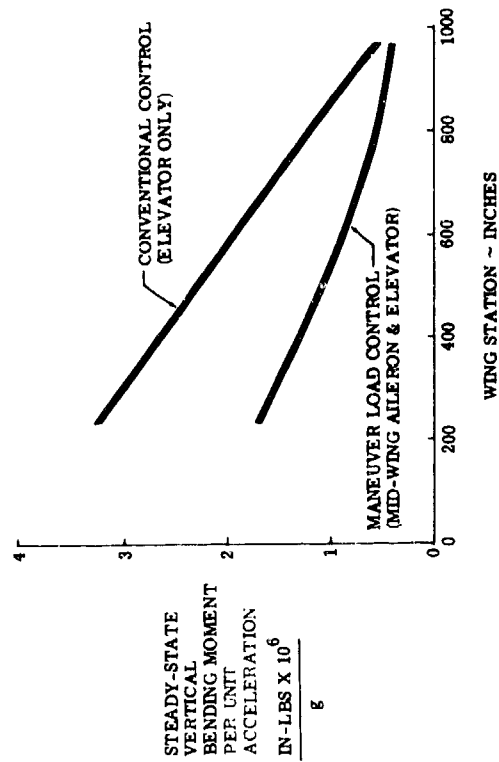
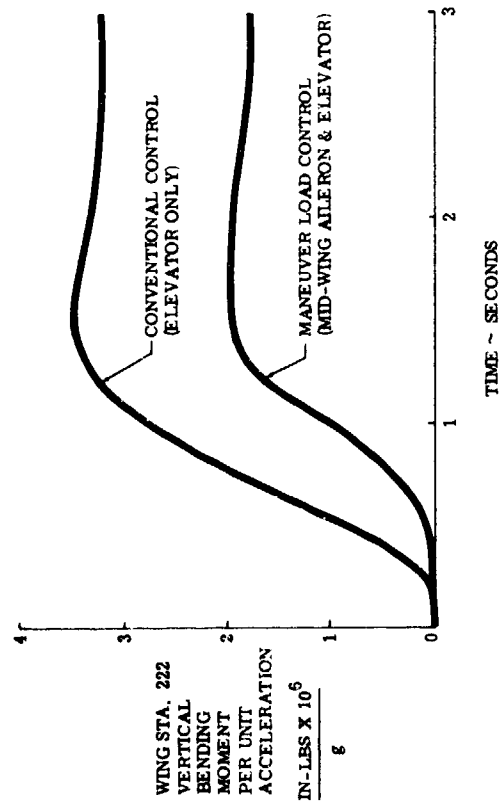
A maneuver load control concept was developed for the B-52 using a midwing aileron and the existing elevator. Maneuver commands to the elevator and aileron are gain scheduled and passed through feedforward low pass filters to prevent excitation of wing structural modes.

The left chart illustrates the reduction in peak inboard wing loads (WS 222) in response to a ramp control column command. Peak loads at the wing root are reduced over 50 percent.

At the wing root, maneuver load control reduces steady state wing loading over 50 percent as shown by the right chart.

WING ROOT BENDING MOMENT WITH MANEUVER LOAD CONTROL

B-52F
400 KEAS
222,000 POUNDS
2,000 FEET

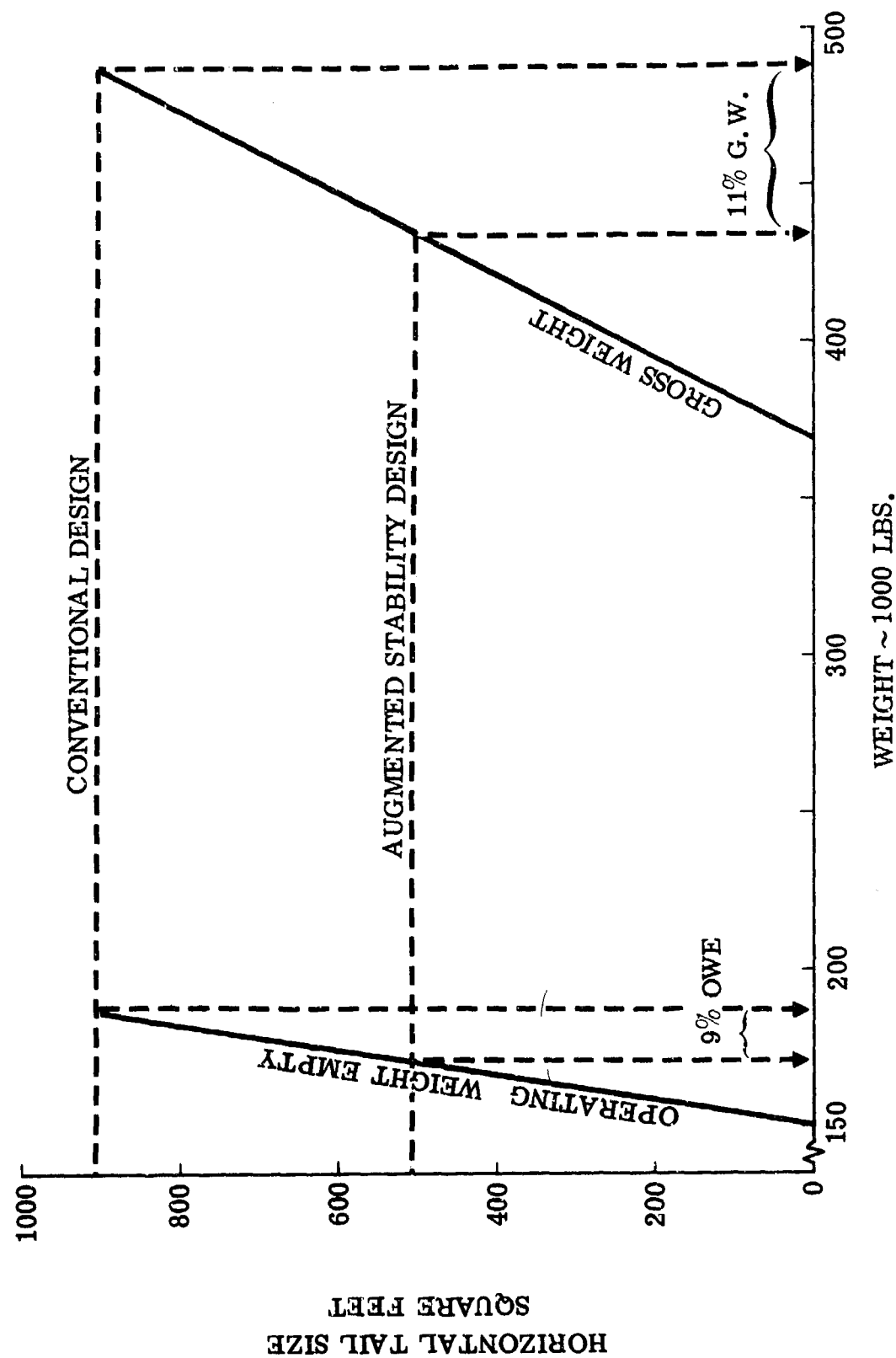


AUGMENTED STABILITY

Studies have been conducted to determine potential weight savings available by relaxing aircraft inherent stability. Presently, an empennage is sized by static stability considerations, and tail surfaces are sized to provide a specified inherent static stability at the most aft cg condition. By relaxing this requirement and augmenting the stability with a control system, tail surfaces may be smaller and aft fuselage gust load requirements less.

This chart compares aircraft weights as a function of horizontal tail size for a conventional design and an augmented stability design for a B-52 class airplane and a constant mission. The augmented stability design has a potential weight savings of 67,000 pounds of structural weight as a result of reduced horizontal tail size and reduced aft fuselage structural weight.

AUGMENTED STABILITY POTENTIAL BENEFIT



1G700988-6

Analyses have been conducted to determine ride improvement from relaxing the inherent directional stability of an aircraft.

This chart illustrates the effect of reducing the vertical tail size on lateral acceleration. A B-52 free airplane condition is shown on the left, and the same B-52 condition with a conventional Dutch roll SAS is on the right. The SAS provides a Dutch roll damping ratio of 0.6 and a damped frequency of 1.2 radians per second for both tail configurations. The data is for a B-52H airplane at a gross weight of 350,000 pounds, 4,000 feet altitude and 370 knots calibrated airspeed.

Reducing the free airplane vertical tail size by 50 percent reduces lateral acceleration at the aft bulkhead 57 percent, although pilot acceleration is increased 16 percent.

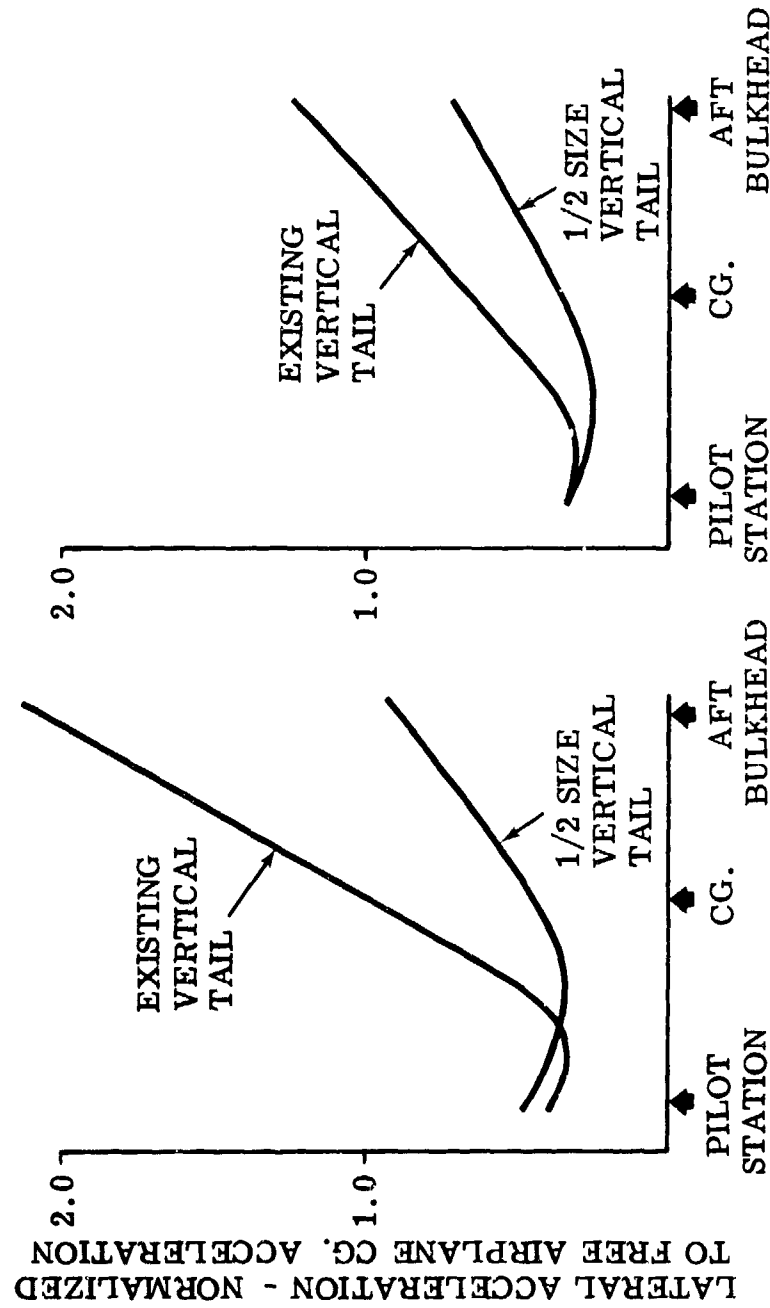
With the SAS, a 50 percent reduction in tail size reduces lateral acceleration 43 percent at the aft bulkhead.

EFFECT OF RELAXED DIRECTIONAL STABILITY ON B-52 LATERAL ACCELERATION

GW - 350,000 POUNDS
ALT - 4,000 FEET
VEL - 370 KCAS

FREE AIRPLANE
($\zeta = .14$)

WITH SAS
($\zeta = 0.6$)



NOTES

CONCLUSION

"IT IS BECOMING APPARENT THAT THE CONTROL SYSTEMS OF OUR MODERN COMPLEX AIRCRAFT CAN BE POWERFUL TOOLS TO HELP SOLVE PROBLEMS OTHER THAN CONTROL OF THE FLIGHT PATH. THROUGH PROPER SENSORS, THEY CAN BE USED FOR GUST ALLEVIATION, FLUTTER MODAL SUPPRESSION, AS WELL AS FOR AUGMENTATION OF THE BASIC STABILITY OF THE AIRPLANE. IT MAY WELL BE THAT THROUGH SUCH SCHEMES, THE STRUCTURAL WEIGHTS OF FUTURE COMPLEX AIRCRAFT CAN BE REDUCED AND THE PERFORMANCE POTENTIAL OF THE AIRPLANE IMPROVED."

DEAN COURTLAND D. PERKINS
PRINCETON UNIVERSITY

7TH VON KARMAN LECTURE, AIAA, 1969.

NOTES

REFERENCES

B-52 G/H Stability Augmentation Program

1. D3-6434-1, "Critical Analysis of B-52 Stability Augmentation and Flight Control Systems for Improved Structural Life, Part I, Initial Feasibility Study (Yaw Axis Analysis), " 21 December 1964, Wichita Division, The Boeing Company.
2. D3-6434-2, "Critical Analysis of B-52 Stability Augmentation and Flight Control Systems for Improved Structural Life, Part I, Initial Feasibility Study (Roll Axis Analysis), " February 1965, Wichita Division, The Boeing Company.
3. D3-6434-3, "Critical Analysis of B-52 Stability Augmentation and Flight Control Systems for Improved Structural Life, Part I, Initial Feasibility Study (Pitch Axis Analysis), " February 1965, Wichita Division, The Boeing Company.
4. D3-6434-4, "Critical Analysis of B-52 Stability Augmentation and Flight Control Systems for Improved Structural Life, Part I, (Analysis and Synthesis of Advanced Stability Augmentation Systems), " August 1965, Wichita Division, The Boeing Company.
5. D3-6434-5, "Critical Analysis of B-52 Stability Augmentation and Flight Control Systems for Improved Structural Life, Part I, (Analog Computer Simulation), " August 1965, Wichita Division, The Boeing Company.
6. D3-6950, "Stability Augmentation System Analysis, " 29 September 1967, Wichita Division, The Boeing Company.
7. D3-6951-2, "Dynamic Analysis and Structural Performance Evaluation of ECP 1195 Prototype Stability Augmentation System, " 7 February 1967, Wichita Division, The Boeing Company.
8. D3-6951-6, "ECP 1195 Prototype - Flight Test Structural Demonstration and Loads Evaluation, " 21 November 1967, Wichita Division, The Boeing Company.
9. D3-6953, "Aerodynamic Characteristics and Flying Qualities ECP 1195 Prototype, " 25 September 1967, Wichita Division, The Boeing Company.
10. D3-7096, "Auxiliary Actuator Servo Load Investigation for B-52 ECP 1195 Program, " June 1966, Wichita Division, The Boeing Company.

11. D3-7200, "Dynamic Loads Reconstruction of Spanish Peak Gust Profiles, Airplane B-52H 61-023," 15 December 1966, Wichita Division, The Boeing Company.
12. D3-7444, "Analog Computer Investigation of B-52 Hydraulic Power Control for Rudder and Elevator - ECP 1195 Prototype," July 1967.
13. D-13273-379A, Volume I and Volume II, "Prototype Stability Augmentation and Flight Control System Evaluation - B-52G & H (WFT 1301) - Final Flight Test Report," 28 November 1967, Wichita Division, The Boeing Company.
14. Austin, William H., "Environmental Conditions to be Considered in the Structural Design of Aircraft Required to Operate at Low Levels," SEG-TR-65-4, Systems Engineering Group, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, January 1965.
15. Dempster, J. B., Roger, K. L., The Boeing Company, "Evaluation of B-52 Structural Response to Random Turbulence with Stability Augmentation Systems," Journal of Aircraft, November-December 1967.
16. Arnold, J. I., The Boeing Company, "Automatic Control for Damping Large Aircraft Elastic Vibrations," NAECON (National Aerospace Electronics Conference), May 1968.
17. Dempster, J. B., Arnold, J. I., The Boeing Company, "Flight Test Evaluation of an Advanced Stability Augmentation System for the B-52 Aircraft," Presented at AIAA Meeting, October 1968.
18. Rohling, W. J., The Boeing Company, "Flying Qualities: An Integral Part of a Stability Augmentation System," Journal of Aircraft, November-December 1969.
19. Newberry, Clifford F., The Boeing Company, "Consideration of Stability Augmentation Systems for Large Elastic Aircraft," Presented to the AGARD Flight Mechanics Panel, Marseilles University, 21-24 April 1969.
20. FTC-TR-67-30, "Air Force Evaluation of the B-52G and H Prototype Stability Augmentation and Flight Control System," February 1968, Air Force Flight Test Center, Edwards Air Force Base, California, AFSC, USAF.

Load Alleviation and Mode Stabilization (LAMS) Program

21. D3-5388, "Capabilities LAMS Test Vehicle," October 1969, Wichita Division, The Boeing Company.
22. D3-6753-1, "Load Alleviation and Mode Stabilization Program," December 1965, Wichita Division, The Boeing Company.
23. D3-7159, "LAMS Requirements Study Report," 15 September 1966, Wichita Division, The Boeing Company.
24. D3-7598, "LAMS Baseline Stability Augmentation System Design," 20 September 1967, Wichita Division, The Boeing Company.
25. D3-7902-5, "LAMS Outer Loop Control System Compatibility Test," December 1968, Wichita Division, The Boeing Company.
26. TR-68-158, "Aircraft Load Alleviation and Mode Stabilization (LAMS)," December 1968, AFFDL.
27. TR-68-161, "Aircraft Load Alleviation and Mode Stabilization (LAMS) B-52 System Analysis, Synthesis, and Design," November 1969, AFFDL.
28. TR-68-162, "Aircraft Load Alleviation and Mode Stabilization (LAMS) C-5A System Analysis and Synthesis," November 1969, AFFDL.
29. TR-68-163, "Aircraft Load Alleviation and Mode Stabilization (LAMS) Flight Test Activities," November 1969, AFFDL.
30. TR-68-164, "Aircraft Load Alleviation and Mode Stabilization (LAMS) Flight Demonstration Test Analysis," December 1969, AFFDL.

31. Johannes, R. P., Burris, P. M., "Flight Controls Damp Big Airplane Bending," Control Engineering, September 1957.
32. Burris, P. M., Dempster, J. B., and Johannes, R. P., "Flight Testing Structural Performance of the LAMS Flight Control System," Presented at AIAA Meeting, March 1968.
33. Johannes, R. P., Thompson, G. O., Kass, G. J., and Dempster, J. B., "LAMS A Technology to Control Aircraft Structural Modes," Presented at 1970 Case Studies in System Control, Sponsored by IEEE Professional Group on Automatic Control, Georgia Institute of Technology, Atlanta, Georgia, June 1970.

Aeroelastic Models

34. D3-7386, "Design Control Specification for a One-Thirtieth Scale B-52E Rigid Model," 10 April 1967, Wichita Division, The Boeing Company.
35. D3-7387-1, "Design Control Specification for a One-Thirtieth Scale B-52E Flexible Model," 15 June 1967, Wichita Division, The Boeing Company.
36. D3-7763-1, "B-52 Aeroelastic Model - Summary Report," 25 April 1968, Wichita Division, The Boeing Company.
37. D3-7763-2, "B-52 Aeroelastic Model - Summary Report," 29 April 1968, Wichita Division, The Boeing Company.
38. D3-7763-3, "B-52 Aeroelastic Model - Equations of Motion and Response Data," 29 April 1968, Wichita Division, The Boeing Company.
39. D3-7763-4, "B-52 Aeroelastic Model - Frequency Response Function Data," 29 April 1968, Wichita Division, The Boeing Company.
40. D3-8390-1, "Analysis and Mechanization of NASA-Langley Flutter SAS Concepts," 21 September 1970, Wichita Division, The Boeing Company.

41. Rainey, A. Gerald and Abel, Irving, "Wind-Tunnel Techniques for the Study of Aeroelastic Effects on Aircraft Stability, Control, and Loads," NASA Langley Research Center, Presented at the AGARD Flight Mechanics Panel Meeting, Marseilles, France, April 21-24, 1969.

Supersonic Transport Stability Augmentation System Trade Studies

42. D3-7600-5, "Supersonic Transport Longitudinal SAS Conceptual Study Results," 6 September 1968, Wichita Division, The Boeing Company.
43. D3-7600-6, "Supersonic Transport Lateral SAS Conceptual Study Results," 1 November 1968, Wichita Division, The Boeing Company.
44. D3-7600-7, "Supersonic Transport Passenger Ride Quality Criteria Analysis Development and Validation Testing Results," 24 February 1969, Wichita Division, The Boeing Company.
45. D3-7600-9, "Supersonic Transport Flutter SAS Conceptual Study Results," 7 April 1969, Wichita Division, The Boeing Company.
46. D3-7600-10, "Supersonic Transport Longitudinal LAMS SAS Conceptual Study Results," 5 May 1969, Wichita Division, The Boeing Company.
47. D3-7600-11, "Supersonic Transport Lateral LAMS SAS Conceptual Study Results," 16 May 1969, Wichita Division, The Boeing Company.
48. D3-7600-12, "Supersonic Transport Moving Base Simulation Controllability Test Results and Criteria Development," 8 December 1969, Wichita Division, The Boeing Company.
49. D3-7600-14, "Supersonic Transport Gust Alleviation and Mode Suppression System Design Criteria," 30 December 1969, Wichita Division, The Boeing Company.

Controls Configured Vehicles (CCV)

50. D3-8264-1, "Benefits of Advanced Flight Control Concepts," April 1970, Wichita Division, The Boeing Company.
51. D3-8355, "Advanced Flight Control Applications and Benefits," June 1970, Wichita Division, The Boeing Company.
52. D3-8440, "Feasibility of an Active Flutter Control Demonstration," December 1970, Wichita Division, The Boeing Company.
53. Holloway, R. B., Burris, P. M. and Johannes, R. P., "Aircraft Performance Benefits from Modern Control Systems Technology," Journal of Aircraft, Volume 7, Number 6, November-December 1970.
54. Pasley, Lewis H. and Kass, Gerald J., "Improved Airplane Performance Through Advanced Flight Control System Design," CASI/AIAA, Toronto, Canada, July 1970.
55. Newberry, Clifford F., The Boeing Company. "The Effect of Active Controls on Structural Responses," Presented to AGARD Structures and Materials Panel, Tøngsberg, Norway, 2-6 November 1970.